VULNERABILITY ASSESSMENT OF CRITICAL OIL AND GAS INFRASTRUCTURES TO CLIMATE CHANGE IMPACTS IN THE NIGER DELTA

A thesis submitted to the Doctoral College, De Montfort University, for the award of Doctor of Philosophy (PhD) in Sustainability and Climate Impact Assessment

By

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ABSTRACT

Oil and gas infrastructures are being severely impacted by extreme climate change-induced disasters such as flood, storm, tidal surges, and rising temperature in the Niger Delta with high. There is a high potential for disruption of upstream and downstream activities as the world climate continues to change. The lack of knowledge of the criticality and vulnerability of infrastructures could further exacerbate impacts and the assets management value chain. This thesis, therefore, applied a criteria-based systematic evaluation of the criticality and vulnerability of selected critical oil and gas infrastructure to climate change impacts in the Niger Delta. It applied multi-criteria decision-making analysis (MCDA) tool – analytic hierarchy process (AHP), in prioritising systems according to their vulnerability and criticality and recommended sustainable adaptation mechanisms.

Through a critical review of relevant literature, seven (7) criteria each for criticality and vulnerability assessment were synthesised accordingly and implemented in the assessment process. A further exploratory investigation, physical examination of infrastructures, focus groups and elite interviews were conducted to identify possible vulnerable infrastructures and scope qualitative and quantitative data for analysis using Mi-AHP spreadsheet. Results prioritised the criticality of infrastructures in the following order: terminals (27.1%), flow stations (18.5%), roads/bridges (15.5%), and transformers/high voltage cables (11.1%) while the least critical are loading bays (8.6%) and oil wellheads (5.1%). Further analysis indicated that the most vulnerable critical infrastructures are: pipelines (25%), terminals (17%) and roads/bridges (14%) while transformers/high voltage cables and oil wellheads where ranked as least vulnerable with 11% and 9% respectively.

In addition to vulnerability assessment, an extended documentary analysis of groundwater geospatial stream flow and water discharge rate monitoring models suggest that an in-situ rise in groundwater level and increase in water discharge rate (WDR) at the upper Niger River could indicate a high probability of flood event at the lower Delta, hence further exacerbates the vulnerability of critical infrastructures. Accordingly, physical examination of infrastructures suggests that an increase in regional and ambient temperature disrupts the functionality of compressors and optimal operation of Flow Stations and inevitably exacerbate corrosion of cathodic systems when mixed with the saltwater flood from the Atlantic.

The thesis produced a flexible conceptual framework for the vulnerability assessment of critical oil/gas infrastructures, contextualised and recommended sustainable climate adaptation strategies for the Niger Delta oil/gas industry. Some of these strategies include installation of industrial groundwater and water discharge rate monitoring systems, construction of elevated platforms for critical infrastructures installations, substitution of cathodic pipes with duplex stainless and glass reinforcement epoxy pipes. Others include proper channelisation of drainages and river systems around critical platforms, use of unmanned aerial vehicles (UAVs) for flood monitoring and the establishment of inter-organisational climate impact assessment groups in the oil/gas industry. Climate impact assessment (CIA) is suggested for oil and gas projects as part of best practice in the environmental management and impact assessment framework.

PUBLICATIONS ARISING FROM THESIS

i. Udie, J.; Bhattacharyya, S.; Ozawa-Meida, L. A (2018). Conceptual Framework for Vulnerability Assessment of Climate Change Impact on Critical Oil and Gas Infrastructure in the Niger Delta. ***Climate 6***, 11

ii. Udie, J.; Bhattacharyya, S.; Ozawa-Meida, L. (2018). Vulnerability Assessment of Climate Change Impacts on Critical oil/gas Infrastructure in the Niger Delta. *The International Journal of Climate Change; Impact and Response* ***(Accepted September 2018)***

iii. Udie, J., Bhattacharyya, S.C., Ozawa-Meida, L. (2018) Evaluation of Oil/Gas Infrastructure Exposure to Climate Change Burdens in the Niger Delta, Paper presented with an award **(See Appendix XXX, page 339)** from the International Conference on Climate Change: Impact and Responses, University of California, Berkeley, USA, April 2018. http://hdl.handle.net/2086/16178

iv. Application of Multi-Criteria Decision-making Analysis (MCDA) in Vulnerability Analysis of Climate Change Impacts in the oil and gas industry, a case in the Niger Delta. A paper accepted for presentation at the 11th International Conference on Climate Change: Impact and Responses, Catholic University of America, Washington, USA, April 2019.

v. Udie, J., Bhattacharyya, S.C., Ozawa-Meida, L. (2016) Conceptual framework for climate impact assessment of vulnerable oil/gas infrastructure. De Montfort University Doctoral College Poster Competition ***(Poster presentation).***

vi. Udie, J.; Bhattacharyya, S.; Ozawa-Meida, L. Researching Successfully in the Global South, the Niger Delta Perspective **(under review)**

DEDICATION

I dedicate this thesis to my wife – **Eucharia** and daughters - **Awhobiwom and Liyiaunim**, for their perfect understanding and sharing in my regular absence from the beginning to the end of this study.

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Lastly, I salute the encouragement of my colleagues at the Institute of Energy and Sustainable Development (IESD), the Doctoral College and De Montfort University Community. Best of luck to all. Nonetheless, the risk in thanking people is that deserving others don't get mentioned. On this note, I wish to express my warm gratitude to all those whose names might not have reflected on this page.

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Thesis Acronyms

AFO	Annual Flood Outlook
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
AWOS	Automatic Weather Observation Stations
CIA	Climate Impact Assessment
COP 21	Committee of Parties 21
CSR	Corporate Social Responsibility
DCP	Data Collection Platforms
DPR	Department of Petroleum resources
EDG	Emergency Diesel Generators
EGASPIN	Environmental Guidelines and Standards for the Petroleum Industry in Nigeria
EIA	Environmental Impact Assessment
FDI	Foreign Direct Investment
GeoSFM	Geospatial Stream Flow Model
GHG	Greehouse Gases
GMW	Groundwater Monitoring Wells
GRAs	General Restricted Areas
GRE	Glass Reinforcement Epoxy
HVC	High Voltage Cables
IEMA	Institute of Environmental Management and Assessment
IOC	International Oil Companies
IPCC	Intergovernmental Panel on Climate Change
JV	Joint Venture
JVC	Joint Venture Contract
LGA	Local Government Areas
MADM	Multi Attributes Decision Making
MAP	Mutual Assistance Plan
MCDA	Multi-Criteria Decision-making Analysis
MODM	Multiple Objective Decision Making
NEMA	National Emergency Management Agency
NIHSA	Nigeria Hydrological Services Agency
NiMET	Nigeria Meteorological Agency
NOAA	National Oceanic Atmospheric Administration
OFS	Ogbogu Flow Station
OML	Oil Mining Lease
OPEC	Organisation of Petroleum Exporting Countries
PEAR	People, Environment, Assets, and Reputation
POB	Personnel on Board
PTDF	Petroleum Technology Development Fund
QIT	Qua Iboe Terminal
SPDC	Shell Petroleum Development Company
SRP	Seasonal Rainfall Predictions
SWAT	Soil and Water Assessment Tool
TEPN	Total Exploration and Production, Nigeria
UAVs	Unmanned Area Vehicles

CHAPTER ONE

INTRODUCTION OF THE STUDY

1.1 Introduction

This chapter presents the background of the study and insight into the structure, focus, and motivation for the overall research. It sets the pathway for the understanding the underpinning issues on climate science and change in relation to impacts and how these severely affects systems. It is divided into nine (9) sub-sections; 1.1 being the chapter introduction, 1.2, 1.3 and 1.4 contains the background, relevance and statement of the problem. The relevance of the study compares the national and global dependencies on the Niger Delta and argues that the impact of climate change on the oil and gas industry in the region could cascade through supply chains and significantly impact Europe, Asia and the Americas. The overall study aims and objectives are presented in section 1.5 while sections 1.6 and 1.7 explains the research questions and the study gaps. Sections 1.8 and 1.9 contains the structure of the thesis and a summary of the chapter.

1.2 Background of the Study

The climate is a complex system of interactions that affect the atmospheres (layer of gases), hydrosphere (oceans and water bodies), lithosphere (land, rocks etc) and the biosphere which combines other phases and forms where life (including humans) exist and interact. Accordingly, human interaction with the pristine nature of the biosphere through structured investments has negatively impacted on natural ecosystems (Mooney et al., 2009; Stern and Kaufmann, 2014; Jones, 2001a). Human activities such as energy explorations, production, transportation and consumption, agriculture, industrialisation, and transportation emit different gases at different levels and quantities into the atmosphere. These gases such as carbon dioxide, methane, nitrous oxide, chlorofluorocarbon, etc. accumulate in the atmosphere, trap and reflect heat (Zheng et al., 2018; Allen et al., 2013; Rodríguez and Lombardía, 2010). These gases trap heat in excess of normal leading to warming, a phenomenon described as ***Global Warming*** (Wang, Jiang and Lang, 2017; Bondyrev, Davitashvili and Singh, 2015; Hughes, 2000). Global warming has over the years caused the earth to heat up than required, which creates effects including droughts, rapid melting of ice sheets, drying up of lakes and dames and frequent heavy rainfall. The frequency of these occurrences is argued to demonstrate a change in the global climate systems – a phenomenon known as ***Climate Change***. Climate change is the mean variability in weather events such as temperature, wind, precipitation and rainfall over a period of time – usually decades of years (30 – 35 years) (Scholze et al., 2006; Akinwale, 2010; Davidson et al., 2003). However, the global climate structure changes spontaneously due to natural forcing in addition to human interference known as ***anthropogenic effects,*** usually through greenhouse gas (GHG) emissions (Bondyrev, Davitashvili and Singh, 2015; Zecca and Chiari, 2010). Commonly discussed GHGs are carbon dioxide (CO_2) methane (CH_4) and nitrous oxide (N_20) that accumulate in the atmosphere, trapped and re-emit it heat continually into the earth causing unusual warming of the earth (global warming) (Iwata and Okada, 2014; Preston, Jones and Scientific, 2006). *Figure 1* compares the cases of natural heat escape (greenhouse effects) in natural and anthropogenic climate scenarios showing an equal amount of solar radiation towards the earth. It shows less heat escapes to space due to intensified human activities (anthropogenic scenario). Less escape of heat into space with continual solar radiation causes the earth to warm more than normal with the capacity to change the climatic system. A phenomenon known as climate change (Zhao et al., 2017a; Fischer and Knutti, 2015; Schmidt, 2010; Van der Mensbrugghe, 1998).

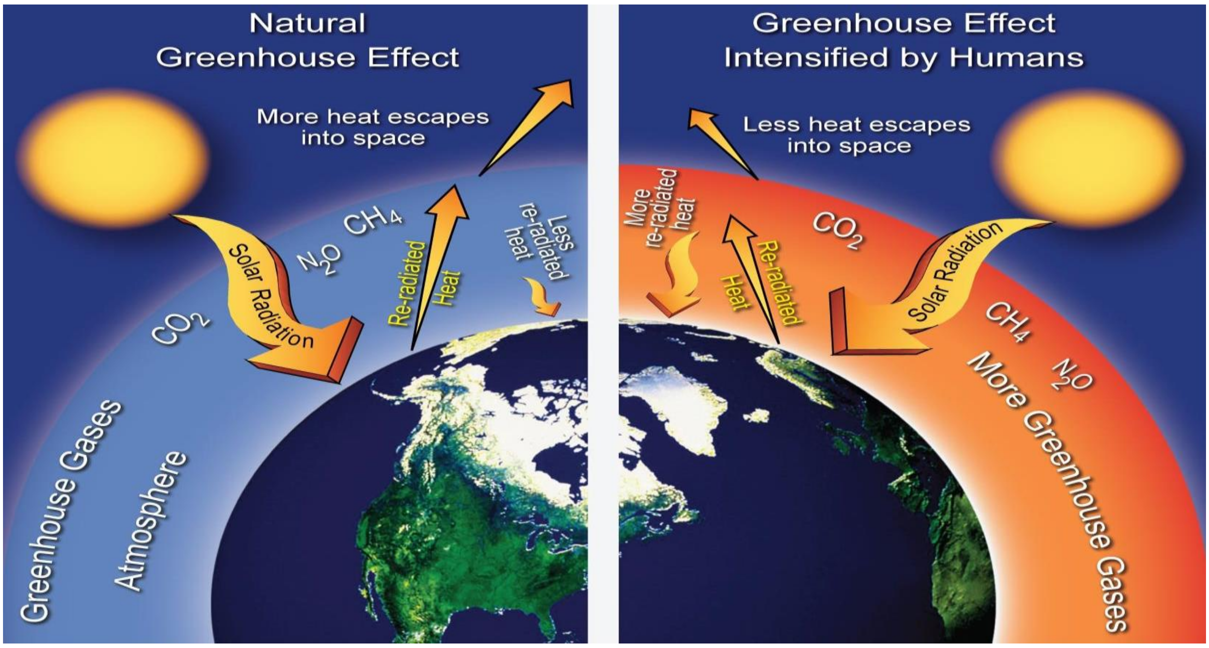

Figure 1; Anthropogenic Effect of the greenhouse effect on the atmosphere. Source: (Koehrsen, 2017)

However, solar radiation reaching the Earth is either reflected into the atmosphere or absorbed by the earth surfaces. It is argued that the earth's albedo (percentage of reflective capacity of incident light) is 30% implying that 70% of solar radiation that reaches the earth surface is retained to exacerbate warming and climate change (Shields et al., 2013; EPA, 2018).

Climate change is seen as the major global environmental threat facing almost every aspect of human endeavour. It is orchestrated by a rise in global average temperature by 0.6˚C and 0.9° within the last century (Tingley and Huybers, 2013; Parry, 2007). It was initially contended that within the past two decades, 2015 was the warmest year (average of 1.62°C) but recent statistics showed that 2016 was the warmest (1.69°C) annual temperature. This has remained consistent since 2014 and is set to continue into the century. It is argued that January and February 2016 global average temperature was 1.15°C and 1.35°C respectively higher than 20th-century averages and the highest for the month of January/February in the past 137 years (The Guardian, 2016). It is further stressed that atmospheric temperature could rise within the range of 1.4˚C to 5.8˚C by the year 2100 with the global climate expected to change significantly (Pachauri et al., 2014).

The Arctic and Greenland ice sheets are rapidly melting due to the increase in global average temperature and it is expected to cause a proportional rise in sea levels. The Arctic ice has steadily reduced especially within the last 20 to 40 years emptying in high volumes into the ocean (Pittock et al., 2011; Pittock, 2013; Ma et al., 2011). Increased river and sea volumes frequently cause flooding of coastal areas, rivers, estuaries deltas, and alluvial plains disrupting economic activities. These changes are projected to continue with expected severe impact mostly on the global south. These impacts have attracted global attention in recent times, with the United Nations advancing debates on adaptation and mitigation at a global scale. In Africa, the tendency of impact is argued to be enormous unless pragmatic awareness and adaptations are planned and executed to curb the effects (Jamali and Karam, 2018a; Morton, 2007; Linnerooth-Bayer and Mechler, 2006). The gravity of impacts will depend on the level of adaptation strategies available and preparedness, growth and continued global demand for fossil energy. However, it is argued that the fossil energy sector contributes 65% of global CO_2 emission and its projection for growth implies more forcing of global warming (McGlade and Ekins, 2015; IPCC, 2014). But with advances in technology, emissions from fossil companies could be reduced

Recent extreme events arising from sea level and temperature rise have caused extreme flooding and droughts all over the world. These incidences have raised serious concerns of vulnerabilities of sensitive systems and critical infrastructures that could cascade severe consequences on world economies. These impacts threaten geographical locations such as coastal areas and shorelines where sensitive regions (such as the Niger Delta) could be disrupted. The disruption of the Niger Delta has the tendency of affecting oil and gas activities and exacerbates various vulnerability patterns that could impact on the Nigerian Economy. The Niger Delta is one of the crude oil and gas exploration and production hubs in Sub-Saharan Africa. As a result, most oil and gas facilities that support both local and national economies are in this region. The Nigerian economy depends largely on oil and gas trading at about 40% of GDP and 90% of government expenditure is generated from fossil energy sales (Tami and Moses, 2015; Sanusi, 2010; Calderón and Servén, 2010). In addition to the regional dependence of West Africa on the Nigeria gas through the regional gas pipeline (*Figure 3*), crude oil and Liquefied Natural Gas (NLG) are frequently being exported to other parts of the world including America, Asia and Europe (*Figure 2*). This implies that the impacts of climate change on infrastructures could severely affect Nigeria, West Africa, Asia and other Western economies such as India, South Korea, Japan and the Netherlands.

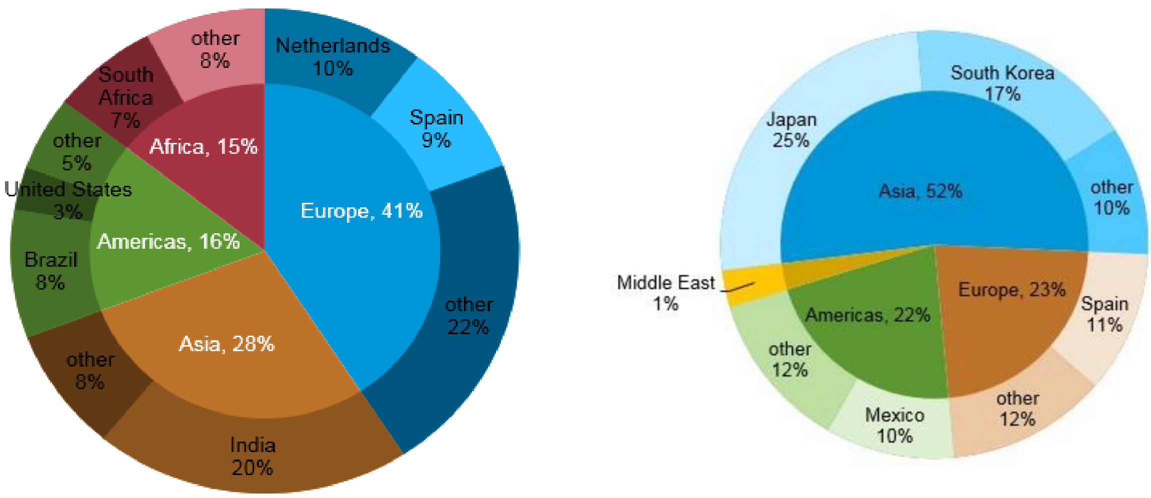

Figure 2; Nigeria's Crude oil and NLG export by destination 2015. Source: EIA (2015)

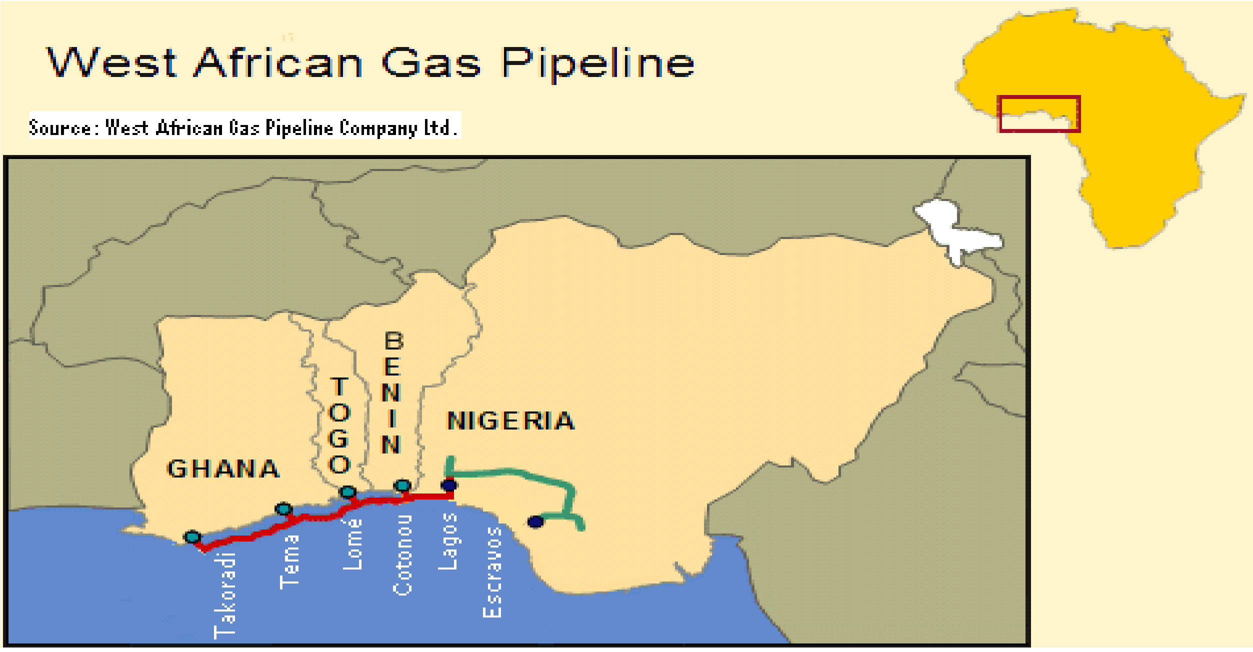

Figure 3; West African Gas Pipeline emanating from the Niger Delta, Nigeria; Source: EIA (2015)

1.3 Relevance of the study

As stated earlier, the oil and gas industry and its infrastructures play a crucial role in the global economy. It connects investors and consumers of products and services including agriculture, water resources, land use, power, as well as transport from across the world. Goldthau (2014); Hunt and Watkiss (2011) argued that the overall infrastructure stock of an economy constitutes about 70% of total GDP and should be protected from environmental and social disasters. The oil and gas infrastructures are at the epicentre of global system hierarchy next to transport and telecommunication systems which conveys economic developments. The criticality of these systems, therefore, justify the relevance of study which aimed to assess the vulnerability and criticality of oil and gas systems to climate change impacts. Furthermore, IPCC (2007) warned that to maintain a high infrastructure profile, about $1.6 trillion USD or 1.5% of the World's GDP would be spent on resilience due to the impacts of climate change. It argued that more financial investment will be required now and even more by the year 2035 to adapt systems sustainably to climate impacts. It further claimed that to prepare for the worst conditions of climate change, an extra $1.6 trillion USD would be needed in energy-related investments globally. These increases the relevance of this study with the view to providing theoretical evidence for adaptation planning, at least for oil and gas infrastructure.

Larsen et al. (2008) when assessing climate impact on Alaska public infrastructure, concluded that public infrastructures are at risk of climate change. Alaska, like the Niger Delta, is a US fossil energy hub which hosts relevant oil/gas infrastructures. However, Larsen *et al.* (2008) further argued that climate conditions vary from region to region and impact infrastructures differently; hence, the importance of establishing variable degrees of vulnerabilities and adapting assessment models to local vulnerabilities and adaptation strategies. While their argument presents a justification for vulnerability assessment in the context of the Niger Delta, it implies that assessment methodology and suggested adaptation strategies may vary according to prevailing risks in the region.

The relevance of this study could also strengthen the need for critical economic infrastructure protection from the impacts of climate change and other natural disasters. The study aimed to also promote investment in adaptation infrastructures, particularly in fragile Niger Delta coastal ecosystems. It is claimed that severe impacts of climate change due to frequent flooding, storms and other extreme weather events would constitute a serious burden on coastal Niger Deltas (Nzeadibe et al., 2011). Further estimates indicate that 85% of global deltas are currently experiencing severe flooding submerging about 260,000 km^2 of initial land while 50% of their surface area could become more vulnerable within the 21st century (Syvitski et al., 2009; Syvitski, 2008). The significance of this study, therefore, is that it investigates how oil and gas infrastructure could be vulnerable and suggest pragmatic adaptation options against flood, temperature and storm surge impacts in the Niger Delta.

More so, sea level rise is contended to be the greatest climate threats of the 21st century, as it would threaten low-lying inundated coastal areas, deltas, and small island states (Petzold and Ratter, 2015). As most economies depend on crude oil for foreign direct investment and foreign exchange, the relevance of this study is also centred on continual assurance for foreign direct investment (FDI) flows into Nigeria. For example, continue to ensure that the economy remains stronger and viable amidst climate change impacts while the struggle for conversion to green energy thrives.

Nevertheless, government agencies globally emphasised implementation of Environmental Impacts Assessment (EIA) as a prerequisite for oil/gas contracts with less consideration for how the environment could impact the industry. The consequences of climate change call for serious consideration of environmental impacts on businesses in addition to EIA. How the environment can affect oil and gas companies is often not mentioned in contracting, making climate impact assessment a novel construct for the industry. This study would focus on developing a framework that shows how oil/gas companies and policymakers could incorporate climate impact and vulnerability assessment as part of environmental impact assessment. This would ensure that the environment is protected by the business as much as business is protected from environmental impacts. Incorporation of climate impact assessment (CIA) and its statement in IEA reports is considered organisational best practice by international environmental organisations such as IEMA (Bond, Fischer and Fothergill, 2017; Enríquez-de-Salamanca, Martín-Aranda and Díaz-Sierra, 2016). Incorporating CIA in assets management is a strategic approach to ensuring customers and investor's confidences in the oil/gas business is maintained.

1.4 Statement of the problem

Severe weather changes, storms and rising sea levels are negatively impacting people, businesses and infrastructural development globally and their infrastructures are more vulnerable (Pittock, 2017; Altieri and Nicholls, 2017; Hart and Feldman, 2018). Coastal areas and deltas all over the world, especially in developing countries, are contended to be at risk of climate change impacts (Adelekan, 2010; M. Smith et al., 2002). Nigeria's critical oil/gas infrastructures are in the Niger Delta coast. With the dwindling crude oil prices, oil/gas revenue still constitutes about 90% of government's annual budget and revenue (Hassan and Kouhy, 2013), therefore, the vulnerability of oil/gas infrastructures to flood, storm surge or other climate-related disasters could pose a significant national economic problem.

Ologunorisa and Tersoo (2006) reported that Nigeria had witnessed her worst flood after 50 years in 2012 and more than 10% of export trade was affected as 6 - 7 cargoes (1.39%) carrying 1 million barrels of crude oil were delayed. Furthermore, an estimated reduction of 500,000 barrels (20% of 2.3 mbd of crude oil) was recorded due to flood impact on the Niger Delta. The predicted sea level rise is likely to displace 30 million people and very likely to submerge about one-fifth of land most especially in the delta regions of the globe (Adelekan, 2011). This impact could disrupt oil/gas infrastructures and cascading impacts on the wider economy. Adelekan (2011b) further argued that the impact of the 2012 flood event was due to misinformation, poor planning and absence of adaption. However, the lack of sustainable adaptation strategies in place combine with a lack of awareness of flood and other coastal disasters associated with climate change creates a problem for the vulnerability of the industry.

1.5 Research aim and Objectives

1.5.1 Research aim

The overarching aim of this research is to assess the vulnerability of critical oil and gas infrastructures to climate change impacts in the Niger Delta. The study also aims to identify sustainable adaptation strategies required to build resistant and resilient infrastructures. To achieve these aims, the following objectives were advised:

1.5.2 Research Objectives

i. To review the potential impacts of climate change on oil/gas operations in the Niger Delta
ii. To systematically review the criteria for criticality and vulnerability assessment of oil and gas infrastructure
iii. To develop a conceptual framework for vulnerability assessment of oil and gas infrastructures
iv. To prioritise selected oil/gas infrastructures according to their criticality
v. To evaluate the vulnerability of critical infrastructure to climate change impacts
vi. To suggest sustainable climate adaptation strategies for oil/gas infrastructures in the Niger Delta

1.6 Research Questions

From the research objectives, the following questions were addressed in this study;

i. What are the potential impacts of climate change on oil and gas operations in the Niger Delta?
ii. What criteria could be implemented for criticality and vulnerability assessment?
iii. How can vulnerability be systematically assessed in the Niger Delta oil and gas infrastructure?
iv. How can oil and gas infrastructure be identified and prioritised according to criticality?
v. Which are the most vulnerable components of the oil and gas critical infrastructure in the Niger Delta?

vi. What are the possible adaptation strategies for protecting vulnerable critical oil and gas infrastructures in the Niger Delta?

1.7 Research Gap

The phenomenon of climate change is expected to trigger some adjustments in industry practices across all sectors of the Nigerian economy. It has triggered the need for design adaptations specifically for the oil/gas infrastructures located in a fragile ecosystem. Though climate change is widely discussed in the industry, the concept of vulnerability assessment and sustainable adaptation planning appears to be challenging and under-estimated in Nigeria. The cost of climate impact and adaptation to projected global increased temperature, sea level rise, storms and heavy downpours is not known. This could seriously hinder the effective planning and execution of national economic policies.

Furthermore, approaches for analysing climate change impact data are not uniform for all cases implying that findings from any given study are not applicable to all systems and locations. For instance, (Schaeffer et al., 2012) faulted the approach used by experts in analysing climate events alleging that the results are no longer efficient and fit for purpose due to climate uncertainties. He argued further that there is an adaptation gap between climate impact and energy infrastructures (mostly) in developing countries. This implies that the assessment of climate impact on energy systems is a relatively new area that could bridge the knowledge gap between adaptation, climate risks and impact in the Niger Delta.

1.8 Thesis Structure

This thesis is structured in nine (9) chapters, each focusing on specific study themes aimed at addressing the research questions. A synoptic content of each chapter is presented below:

Chapter one provided an overview, background, relevance, rationale of the study and the statement of the problem. It also contains the study aims, objectives, research gaps and questions to be addressed.

Chapter two presents a literature review of existing studies in the subject areas. It is structured in 6 subsections; sections 2.1 and 2.2 focuses on general literature of climate change and description of the study area. Sections 2.3, 2.4 and 2.5 present a systematic literature review that illuminates the criteria of assessments while section 2.6 summarises the chapter.

Chapter three presents the designed conceptual framework and its summary. The framework is the structure and pattern of the study from an empirical perspective.

Chapter four contains a detailed description of the study methodology, shows how oil and gas companies were accessed for data collection in the Niger Delta context. It also explains interview designs and how Multi-criteria Decision-making Analysis (MCDA) tool – the Analytic Hierarchy Process (AHP) was implemented.

Chapter five presents a detailed reflection of fieldwork outcomes, challenges from researching in the Niger Delta such as bureaucracy, cultural, and security issues. It describes how informal strategies were applied for data collection from the oil and gas companies.

Chapter six of the thesis contains the analysis of results structured in three sub-sections. The first sub-section analyses the criticality of selected infrastructure based on the criteria from chapter two while sub-section two, present the vulnerability analysis of critical infrastructure. Sub-section three focuses on documentary analysis that supports the outcome of other sections.

Chapter seven presents the review and analysis of adaptation alternatives (structural, institutional and responsive) for the protection of vulnerable critical infrastructure in the study area.

Chapter eight – Discussion and implication of findings, describes the commercial aspects of findings and underpins issues emerging from the study. It also highlights on informal approaches in researching the Niger Delta and discuss the case of the vulnerability of the Oil Mining Lease (OML) 58 compared with its adjacent field. The chapter also narrates how temperature could disrupt the operations of Flow stations, hence impact on maximum operations for temperature dependent systems.

Chapter nine presents the conclusions of the entire study including recommendations for implementation of outcomes in the oil and gas industry and opportunities for further studies.

1.9 Chapter Summary

This chapter presented the background, aims and objectives of the study. The relevance of study is drawn from the importance of oil/gas revenue to Nigeria economy and the dependence of West African and global economies on fossils from the Niger Delta (41% crude and 52% LNG export to Europe, 28% and 16% is export to Asia and America). Protection of the critical infrastructure supporting crude oil production to sustain trade routes and foreign direct investments is crucial and formed the main rationale for this study. In addition, climate change is also discussed as the main reason for the study due to its impacts from flood, windstorms, rising temperature, etc. implementation of sustainable adaptation practices could prevent and reduce the impacts of climate-related disasters on critical infrastructures. Resilient and resistant critical infrastructure implies a robust economic perspective in Nigeria.

CHAPTER TWO
LITERATURE REVIEW

2.0 Introduction

This chapter presents a review of existing studies on climate change, impacts and adaptation. It is structured in four sections. Section 2.0 describes the introductory scope and structure of the chapter. Section 2.1 presents a critical general overview of climate change impacts from their causes, cost, severity and vulnerability. Section 2.2 offers the rationale for the choice of the study area – the Niger Delta. Section 2.3 presents a structured systematic literature review of delineated 53 peer-reviewed journal articles, to stratify the criteria implemented for the criticality and vulnerability assessment of infrastructures. The criteria are further synoptically reviewed in sections 2.4 and 2.5 respectively while section 2.6 contains the chapter summary.

2.1 Literature Overview

2.1.1 Overview of Climate Change

Global climate is argued to be changing especially beginning from the 20th century which witnessed extreme weather such as high temperatures, flooding, and severe storms (Bazerman, 2006). Generally, the global climate has shown reasonable changes in precipitation, sea levels and increase in temperature but, these changes are occurring more frequently than expected and recorded in human history (Burkett et al., 2008; Carey, 2007). Notwithstanding, there are sceptics who argued strongly that the global climate is not changing, thereby promoting a do nothing or little culture on climate issues across industries.

The Inter-Governmental Panel on Climate Change (IPCC) argued that "Global Warming is happening, and contended to have commenced since about 1950, after which observed changes continue over decades. Researchers have argued that the man's activities are responsible for climate change which is in turn challenging human existence (Caney, 2005; Carlsson-Kanyama, 1998; Elias and Omojola, 2015). The concern is that both natural and anthropogenic activities that forced the changing climate are still occurring (Ibid). The effort to curtail these activities (release of CO_2, CH_4, and N_2O) appears seemingly challenging even as take-off point (mitigation and clean energy phenomenon) is often politicised. While these issues are being debated, the need for adaptation planning might be the best practice for sensitive sectors of the economy. It appears obvious from the existing theories and empirical evidence to be discussed in subsequent sections that anthropogenic causes of global climate change are more significant (Odjugo, 2009). Naturally, GHGs have the ability to reflect the amount of heat from the sun as well as absorb some quantity which is emitted to keep the earth warm at an average temperature of 15°C. The higher concentrations of GHGs in the atmosphere, the higher is the rate of heat trapped; the higher the earthly absorption and the higher the rate of global warming (Iwata and Okada, 2014).

Increased global temperatures warm the earth surfaces – including water bodies and land (Hill et al., 2001). Experts and academic theories gathered from climate monitoring over the past century and long-term observations confirm that the earth is warming (De Richter and Caillol, 2011; Jorgenson, 2006; Pielke and Pielke Sr, 2010). Nonetheless, though the climate could change over a long period of time, anthropogenic emissions have exacerbated the impact causing frequent occurrences. What therefore can be implemented to curb this? Anthropogenicity is argued to be implicate leading and industrialised economies with high greenhouse gas emission rate that often attempt to politicise mitigation and adaptation debates (Dimitrov, 2016). The politics of climate change could pose a negative impact on mitigation and affect how vulnerable countries deal with energy use, economic planning and adaptation options. However, the current pattern of warming and changes in annual rainfall volume in the Niger Delta demonstrates beyond politics and requires urgent mitigation and adaptation strategies (Uyigue and Agho, 2007). These strategies are crucial and instrumental to economic progress in the nearest time but what causes the global climate to change?

2.1.2 Causes of Climate Change

Two major causes of climate change have been established. One cause is related to natural changes and variability in the atmospheric conditions over a long period of time, while the other is human induced. Recent human activities since the industrial revolution and continual exploration, production, transportation, and consumption of fossil energy are said to cause the warming of the earth, especially within the 20th century. Research revealed that about 41% - 64% of decadal-scale temperature increase is due to GHG emissions (McJeon et al., 2014). In either case, is it right to attribute the impact of climate change such as hurricanes at the Northern Atlantic within the last decades to human factor? Since the causes of climate change may appear complementary, heaping the entire blame on anthropogenic emissions might appear to an extent hasty; especially to the oil/gas businesses. This could undermine the consideration of natural forcing on the climate and or even considered a political way of downplaying oil-rich economies such as Nigeria (Mann and Emanuel, 2006; Knight et al., 2005).

However, studies in China revealed that warming within the last 50 years could have been caused by increased accumulation of anthropogenic gases in the atmosphere but claimed that the temperature change within the first half of the 20th century was due to “solar activity, volcanic eruptions and sea surface temperature change” (Ding et al., 2007). It is reasonable to argue that the industrialization of China might have contributed to an increase anthropogenic effect on global warming at a global scale while it is argued that the impact of the global change would fall more on developing countries (Peters et al., 2007). This gives more concern to the Niger Delta situation in a developing state (Nigeria) yet with infrastructures of international interest.

Lorenzoni and Pidgeon (2006) and Borick and Rabe (2010) attempt to exonerate the human factor as a cause of climate change by arguing that the earth has suffered natural changes over time. This could be due to an increase in ocean current and influence of natural entropy in addition to the earth independent warming. However, there are persisting concerns for the Niger Delta infrastructures from both anthropogenic and natural effects. Increased ocean currents, storms and even natural warmings have the tendency of impacting on infrastructures – necessitating adaptation and mitigation planning.

Hansen et al. (2010) argued that CH_4, N_2O, and CO_2 trends from fossil gas flaring have significantly increased since 2014 (see figures 4). They argued further that if the effort is made at reducing both non-carbonic and CO_2 emissions, then anthropogenic forcing would reduce dramatically close to zero in the next 50 years. It is possible that the UN committee of parties could have proposed sanctions on fossil energy consumption as principal approaches of climate mitigation (Dimitrov, 2016). This and the argument of Hansen et al (2010) implies that researching adaptation strategies to protect the oil/gas infrastructure is not worthwhile. Nonetheless, there is validity in the argument as fossil energy consumption emit greenhouse gases, but the implementation of sanctions may take longer to achieve a tangible result. Nonetheless, alternative energy options are rapidly emerging in the energy market and could challenge the commercial use of fossil fuels but complete migration to commercial use of alternative energy is capital intensive. Technical, market availability, political, regulatory and environmental barriers constitute the challenges for rapid thrive of renewable alternatives (Evans, Strezov and Evans, 2009; De Luca et al., 2018). By implication, fossil energy consumption may continue far into the century with corresponding emissions levels; making adaptation and mitigation research imperative.

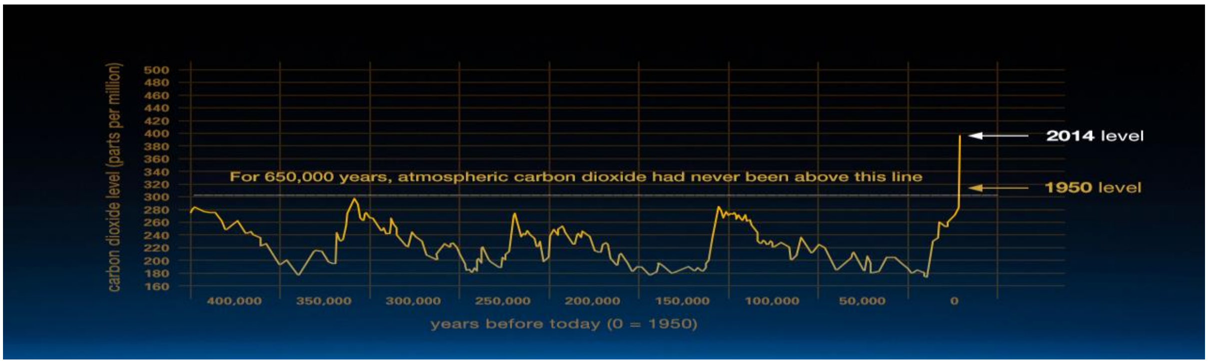

Figure 4; a trend of anthropogenic (CO2) emissions up to 2500. Source: Andrea Thompson (2014)

2.1.3 Climate Projections

Different models have shown projected climate change with some discrepancies in their estimates but have caused the need to consider uncertainties in adaptation planning. This has broadened the scope of climate adaptation strategies to include a cost factor (Anonymous, 2016; Li et al., 2015; Patidar et al., 2014). The implication of uncertainty indicates that adaptation may consider every climate risk in each area even more carefully for an economic reason otherwise we could be planning for nothing. More so, amplitudes of measurable indices of projections (especially temperature and sea level rise) indicate an upward movement but at different degrees depending on models used. There is an overall agreement that global climate would continue to change (Rahmstorf, Foster and Cazenave, 2012; Mori et al., 2013; Vavrus, Notaro and Lorenz, 2015). In recent times, even climate sceptics and denials seem to relax their campaigns with the conception that climate change is imminent. Probably, this is due to the rate of extreme events and calls from political, business, and religious leaders for moral cum business consciousness against climate impact (Francis, 2015). Some of these indicators are highlighted and discussed to further underpin the need for sustainable adaptation.

2.1.4 Temperature

The fifth assessment report of IPCC projects global mean temperature to rise between 1.4° and 6.4°C by 2100; on low and high emission scenarios respectively (Rahmstorf, 2007). Except under strict mitigation scenario, global average temperature (presently 0.9°C) might scale more than double by the end of the 21st century (IPCC, 2014) (see figure 5 below).

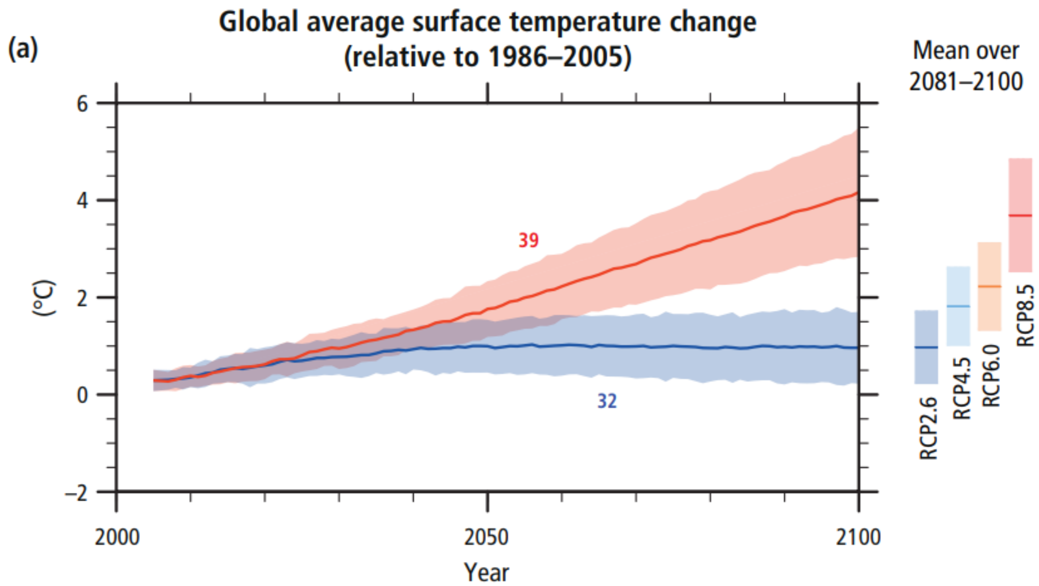

Figure 5; projected global average temperature scenarios. Source: IPCC (2014)

Some climate researchers argued that global warming is likely to scale 2.0°C projected for the 21st century based on computer models. Findings published by the National Oceanic Atmospheric Administration (NOAA) on climate temperature projections suggest that global warming would increase by 1.1 to 5.4°C in 2100. Reason for this increase is blamed on continual greenhouse anthropogenic gases (GHGs) majorly from fossil energy (coal, crude oil, etc) (Hill et al., 2001; Santer et al., 2003). However, the outcome of the 2015 COP 21 agreement in Paris capped global mean temperatures at 2°C by 2100. If this is followed with aggressive mitigation programs, it may contravene initial projections. This would depend on how developing countries can access green energy choices which are already facing criticisms of not being affordable as well as aggressive economic diversification by oil/gas revenue dependent countries. Otherwise, the temperature may increase, sea levels would rise proportionally (Jevrejeva, Moore and Grinsted, 2012; Patidar et al., 2014) subjecting infrastructures and investments around coastal and delta areas to high climate risks.

2.1.5 Sea Level Rise (SLR)

Sea level rise (SLR) is extensively argued as the greatest climate threat of the 21st century (Nicholls and Cazenave, 2010; Grinsted, Moore and Jevrejeva, 2010). It threatens low-lying inundated countries, coastal areas, seaports, deltas and small island states; causing forceful migrations of inhabitants, decommissioning and uninstallations of infrastructure (Dasgupta et al., 2009; Ibe, 1996; French, Awosika and Ibe, 1995). With the Niger Delta as a major host of oil/gas infrastructure in the West African region, concerns are being raised, necessitating prompt actions. However, the causes of sea level rise (SLR) are believed to include thermal expansion of the ocean, melting of Greenland and Antarctic ice caps; depending on the increase in global temperature. The 2007 Intergovernmental Panel on Climate Change (IPCC) Assessment Report projected SLR at 18 - 59 cm (0.18 – 0.59 m) by 2100 (the Grinsted, Moore and Jevrejeva, 2010).

This projection has been contested widely by researchers especially Rahmstorf, (2010); Grinsted, Moore and Jevrejeva (2010) who argued that IPCC physical satellite model failed to capture depletion of the Greenland and Antarctic ice sheet. Rahmstorf (2007) and Vermeer and Rahmstorf (2009) applied semi-empirical models to estimate projections and contended that the rate of SLR depends directly on average global warming arguing further that it would hit 114 cm (1.14 m) and 124 cm (1.24 m) by 2095 and 2100 respectively. These findings have been referred to as reliable by Jevrejeva, Moore and Grinsted (2012) who posit that SLR will hit between 1.02 - 1.9 m by 2100. In either scenario, about 1.3 m average SLR is predicted by the end of the 21st century (see figure 6). However, the implications for a 1.3 m SLR is not clear. As a result, the situation of possible impacts on critical oil/gas systems in Nigeria requires adaptation preparedness through a systematic impact assessment to determine the most vulnerable systems.

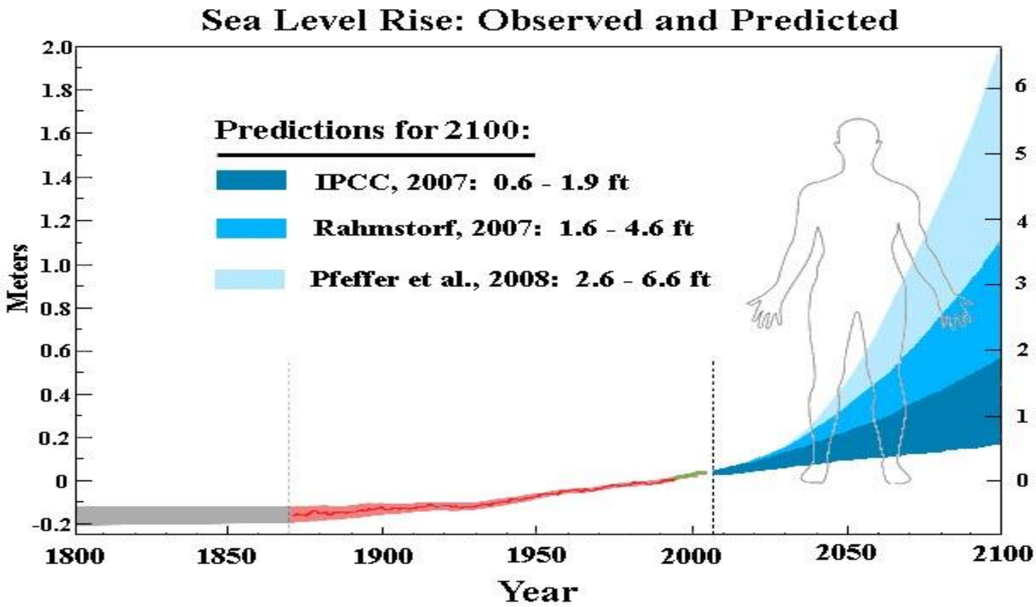

Figure 6; projected global sea level rise; Source: IPCC (2014)

2.1.6 Storm and precipitation

It is argued that temperature and sea levels rise are likely to influence the rate of storms, precipitation and heavy rainfall patterns with negligible uncertainty (Friedlingstein et al., 2014; Deser et al., 2012). IPCC (2007) has it that yet these changes will occur significantly, would vary according to region and season – with some regions having precipitation and storms than others. Melillo et al. (2014) buttressed the argument that annual heavy rain frequency would increase towards 2100. Heavy downpour has become frequent in the Niger Delta, in agreement with the projections of Melillo et al. (2014). Recent events seem to put climate projections in doubt as the rate at which climate-related events occur overrun projections. This may imply that climate scientist needs a pragmatic and concerted effort in overhauling the models used in making estimates to keep up to date with reality. Otherwise, there are chances of under planning which may cause predictable surprises. Heavy downpours and sea level rise are possible threats on deltas and coastal areas (Dasgupta et al., 2009; Adejuwon, 2012) where the critical oil/gas infrastructures in the Niger Delta are concerned. How vulnerable would they be and what measures can be taken to adapt to these changes requires a critical assessment?

Furthermore, Melillo et al. (2014) believed that Atlantic hurricane's intensity is 'likely' to increase given ocean expansion and cause frequent hurricanes. Though hurricanes are not associated with the Niger Delta its location along the Atlantic coast triggered environmental cascading effects on costly critical infrastructures. The objective of this study is, therefore, to investigate the extent of vulnerability and suggest prompt sustainable alternatives in line with future projections.

2.1.7 Cost of Inaction on Climate Change

Climate change poses a serious challenge to businesses and infrastructures (Adelekan, 2010; Chappin and van der Lei, 2014; MacDonald et al., 2009; Odjugo, 2009). Climate change impacts have the capacity to undo the combined progress made in the Niger Delta oil and gas and other industries over decades of years. It could further exacerbate current trend of tsunamis, typhoons, hurricanes, etc. with the tendency of causing food and water scarcity, power outages and energy shortage (Watts et al. 2018; Doan 2016; Johns-Putra 2016). The Niger Delta, South-Eastern US and the Gulf of Mexico (for instance) are hosts to critical pipelines which are vulnerable to intensifying flood and winds resulting in significant disruption of oil distribution (Harvard Business Review, 2016). These impacts come with high-cost implications. Understanding the cost of inaction leads to appropriate and effectiveness in estimating the cost of adaption construct. When the cost of action and inaction are determinable in the Nigeria oil/gas infrastructure context, it creates an opportunity for “No regret” and “precautionary” approaches to be taken; though with special attention to uncertainties (Ahove and Bankole, 2018).

Nevertheless, infrastructure driven organisations and economies argued that climate change inaction is capable of eroding sensitive assets, disrupt market structures and supply chains globally. Environmental disasters resulting from inaction is estimated at $74 trillion at the least (Ackerman and Stanton, 2006; Stanton and Ackerman, 2007). Scorching temperature scenarios could severely affect rigs operations as much as sea level rise could engulf coastal areas. Gulf Coast and other shorelines may disappear (2 feet) by the middle of the century. A prospective loss which academics and practitioners regard as the cost of inaction may place huge burdens on global economic fortunes especially infrastructures. It is suggested that most severe impact would be on infrastructure resulting from rising sea level, storms and heat waves, placing an even high premium on fossil energy as green alternatives remain less affordable (Ackerman and Stanton, 2006). Nonetheless, the price of fossil energy has dropped significantly with a slower reduction in the cost of green alternatives against the postulation of Ackerman and Station (2006). Notwithstanding, climate change burdens now constitute a serious challenge to both oil/gas and renewable energy with significant impacts (Aggarwal, 2008; Bhuiyan, Md Jabed Abdul Naser and Dutta, 2012; Burkett et al., 2008). It is believed that some oil/gas infrastructures in the Niger Delta, constructed around 1956 have lost the resistance needed to withstand climate impact. This could be possible because it was not an urgent issue in the mid-20th century in Nigeria. Furthermore, the need for a sustainable Atlantic coastline is crucial to the government's agenda. Therefore, research to ascertain the cost of vulnerabilities is relevant and worthwhile to the government but not considered in this study.

Nonetheless, there is very skeletal research on climate impact assessment and adaptation planning for critical oil and gas infrastructures in the Niger Delta. This indicates that there is a high likelihood of inaction which could intensify the vulnerabilities of systems. It is argued that inaction especially where certainty is not established could be strategically beneficial and that some experts often get it correct by taking no action (Ruth, Coelho and Karetnikov, 2007). But Odeh (2012) presents a counter-argument on Daily Independent; that the impact of the 2012 flood in Nigeria was predictable yet no action was taken not necessarily as a strategy of minimising cost. Therefore, using climate predictions and available data to estimate the cost of action and inaction of vulnerable infrastructure could trigger actions towards sustainable adaptation planning in a more robust and practical manner.

Furthermore, Balaram (2011) opined that paying attention to critical infrastructure by policy review, rebuilding and updating will be a crucial driver of economic growth in the USA as well as other countries concerned with climate change impact. However, climate adaptation has its cost which if not properly compared, may frustrate the economic fortunes of oil and gas businesses especially when predictions failed. Nevertheless, the benefits of taking no regret and precautionary adaptations outweigh the burdens of inaction by trillions of US dollars (see figure 7).

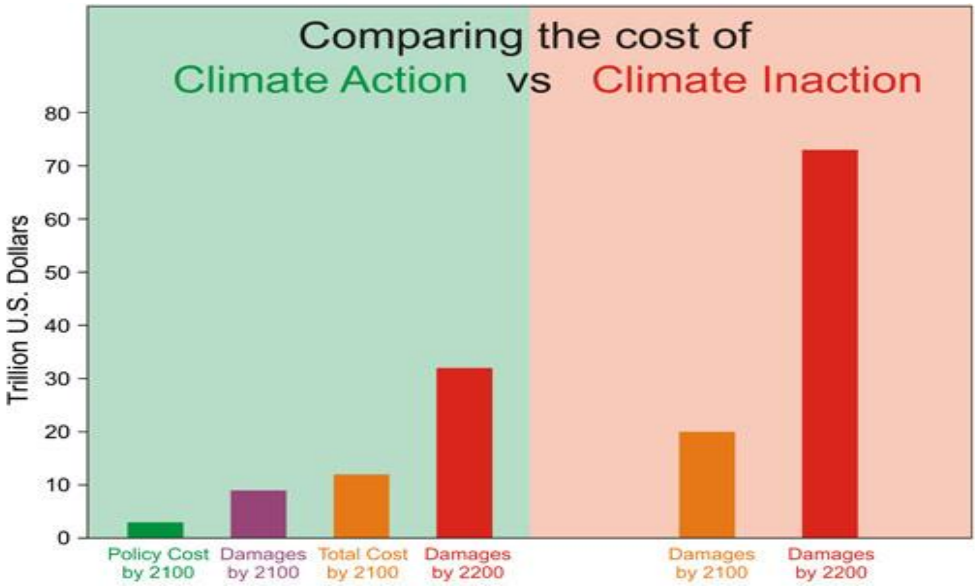

Figure 7; estimated cost of climate action and inaction. Source: sceptical science (2015)

Furthermore, Kemfert and Schumacher (2005) of the German Institute of Economic Research, estimate the global total cost of action on climate change (cost of action) at $12 trillion USD by 2100 while that of inaction (only impact or damages) is estimated at $20 trillion USD. They further estimate the cost of actions to reduce impact at about $30 and $70 trillion US dollars by 2200 as shown in figure 7 above. This literature which though appears outrageous shows that the cost of inaction surpasses ten years of the national budget of most developing economies (including Nigeria). Inaction could have a significant impact on oil and gas companies which are currently under pressure to mitigate and operate sustainably. Therefore, a fraction of the cost of inaction could involve a substantial budget in Nigeria due to the reliance on the oil and gas industry.

Further still, some concerned organisations have developed an interest in estimating the cost of climate inaction. The BBC programme (Outside Source 2015) quoted World Bank and Internally Displacement Monitoring Centre as estimating the cost of climate-related disasters at about $3 trillion USD while 20 million people will be displaced annually in the world. It further claimed that climate change could cost an additional $3.6 – $6.1 billion USD by 2030 and about $5.6 - 7.6 billion USD by 2080, taking into consideration future climate projections. Aguiar et al (2018) however, argued against this claim with the view that strategic adaptation planning could offset the cost by 45%. This seems to strengthen and support this research which proposes that a good knowledge of vulnerable infrastructures could aid an informed investment on cost-effective adaptation alternatives in the Niger Delta.

Nonetheless, the cost of climate change inaction on infrastructure arguably agrees with Stanton and Ackerman (2007) that countries that depend on infrastructure (such as oil and gas assets) are under pressure of dual cost; running the economy and planning infrastructure investment. This research, however, did not investigate the cost of sustainable adaptation strategies for oil/gas infrastructures but suggested some options for the Niger Delta.

2.1.8 What is Climate vulnerability?

Vulnerability in terms of climate change could be seen as the degree or extent to which a system (e.g. infrastructures or coastline) could be susceptible to extreme climatic conditions (Schaeffer et al., 2012; Denner et al., 2015; Birkmann et al., 2013). Other authors define climate vulnerability as "the degree to which a system is susceptible to or unable to cope with, adverse effects of climate change, including climate vulnerability extremes" (J. B. Smith et al., 2009; Jones, 2001b). It also includes the magnitude and rate of occurrences of extreme weather conditions which infrastructures are exposed to in relations to the adaptive capacity and sensitivity of the infrastructures or other systems. The vulnerability could also be viewed from the exposure of the system itself (e.g. NLNG storage plant) and the secondary impact on social life (e.g. settlements and social networks within NLNG storage plant in Bonny Island).

Though vulnerability is defined, most definitions are based on context. According to Holmgren (2004), vulnerability is seen as being sensitive to hazard and threats; stressing further that vulnerability is the combination of negative events that pressurises and substantially reduces the ability of a system to maintain its function. The perspective of Holmgren (2004) seems clearer in underpinning vulnerability of systems. It captures reliability on the capacity of the system, magnitude of impact, period of event and systems criticality. This, therefore, puts vulnerability as a measure of sensitivity or criticality, adaptive capacity, and exposure. However, in real time scenarios, vulnerability may be considered in terms of other factors. When a system is under environmental pressure its capacity to adapt would depend on proximity to risks, impact magnitude etc. such that any further pressure has the capacity to cause damages that will cascade through the value chain (Jenelius, Petersen and Mattsson, 2006).

2.2 Why the Choice of Niger Delta?

It is being contended that the world's largest and economically viable deltas are densely populated and endowed with oil/gas deposits. Hitherto most of the delta dwellers are increasingly becoming vulnerable to climate change impacts such as coastal, river and flash flooding, sea level rise and storms. Coastal Delta's vulnerability is also claimed to result from compaction of sediments due to the extraction of fossil fuels and water from core sediments, semimetal trapping within reservoirs and global sea level rise (Eakin and Luers, 2006; Mmom and Arokoyu, 2010). It is further claimed that 85% of global deltas are experiencing severe flooding which has already submerged 260,00 Km^2 of initial land and it is estimated that 50% of delta surface areas could be vulnerable considering 21st-century climate projections (Syvitski et al., 2009).

Judging from this, what then is the fate of critical oil and gas infrastructures in the Niger Delta in the Nigerian coast? The length of Nigeria coast, spanning from West to East is about 853 KM out of which 51.7% (440 km) is within the Niger Delta. Around the year 2000, it was estimated that 85% of the country's predominantly oil/gas industry and about 100 million people are located or lived along the coastal zone (Badejo and Nwilo 2004**;** Brown, Kebede, and Nicholls 2011). Considering these indices, what could be the impact of climate change and as projected for the Niger Delta? Anyone (1) metre rise in sea level as projected by 2100 may threaten the Niger Delta beyond active rescue disaster management approach, therefore, a proactive vulnerability assessment and adaptation planning could mitigate the threats. Furthermore, in a business as usual approach, about 18,000 Km^2 of the coastal Niger Delta and 3.2 million people (800 communities) could be at high risk of flooding. Taking proactive adaptation measures could be expensive but a necessary choice. For instance, Brown, Kebede, and Nicholls (2011) proposed that protecting on sophisticated oil/gas assets could amount to about USD700 million over a period of five years could cost Nigerian economy 0.2-0.3% of GDP. But the impact of a 'business as usual' approach could be overwhelming. In addition to heavy agro practices, infrastructure has continually evolved in the Nigeria oil and gas Delta since the discovery of crude oil 1956 (see figure 8) when production commenced around the Niger Delta (Watts, 2004).

Secondly, continuous extraction of fossil resources might have created a sedimentary vacuum that may serve as secondary vulnerability opportunities for severe climate impact on oil/gas systems. It is on the bases of the heavy presence on critical oil/gas infrastructures, location along the Atlantic ocean and the role of oil/gas revenue in the Nigerian Economy that justifies the Niger Delta as a perfect research area.

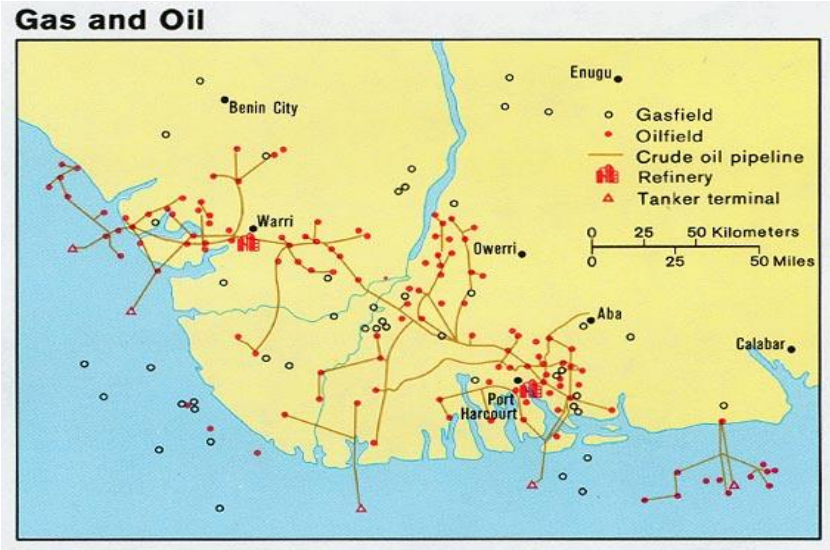

Figure 8; showing oil and gas infrastructure in the Niger Delta. Source; (Musings Maps, 2015)

2.3 Why the Oil and Gas Industry?

Researching the vulnerability of critical oil and gas infrastructures to climate change impacts has raised some concerns in contemporary times. This is because it is argued that about 65% of global CO_2 emissions responsible for warming and subsequent changes in the climate system comes from the oil and gas industry (Koehrsen, 2017; Li et al., 2015; Zecca and Chiari, 2010). This emission includes direct gas flaring and indirect combustion of fossil energy in transportation, electrification and heating, industrialisation and other fussy synergistic sources such as plastic pollution. Based on these arguments, the trend suggests that there is a deliberate attempt to put an end to fossil energy use on a global scale. This trend is further exacerbated by the world drive for sustainability incorporation in businesses ensuring that $C0_2$ emissions are reduced to the barest minimum (Lohrey and Creutzig, 2016). The 2015 UN Paris agreement and Vietnam 2018 Global Warming of 1.5°C reports have continued to force sustainability campaigns, policy direction and attitudinal changes across organisations. As part of the sustainability compliance strategy, the Norwegian government planned to phase out fossil energy powered automobile out of the country by 2020 (The Guardian, 2017). Developing economies and organisations have set emission reduction targets and measurement of carbon footprint. These actions imply that the demand for sustainability and best practices across industries could lead to premature abandonment of the fossil industry. More precisely, the world may run out of crude oil without exhaustive exploration of the global reserves. This could be reaffirming the case of the Stone Age.

Nonetheless, the debate of sustainability, climate change and fossil energy future has attracted both academic research and experts debates in recent times with indication for increasing demand for fossil energy (BP, 2018; Raval, 2017; Bauer et al., 2016; Abas, Kalair and Khan, 2015). In the US, natural gas demand and export have increased within the last five years with high projections into the middle of the century when economic growth is expected globally (Feijoo et al., 2018). Some essential econometrics presents opposing views to the sustainability debate and the claim that the world may [necessarily] run out of crude oil. Energy demand outlooks suggest that though greener alternatives such as the evolving electric cars in the automobile industry, solar PVC heating, etc. could grow amidst a growing dominance of fossil in the world energy market (Raval, 2017). This debate is borne out of the demographic and economic indices of the world population growth trend. It is expected that the world population could reach 9.8 billion by 2040 and 11.2 billion by 2100 with most of this growth occurring in China, India and Africa (United Nations, 2017). This growth could pressurise energy demand which is apparently above alternatives to crude oil.

More so, the Organisation of Petroleum Exporting Countries (OPEC) contended that population growth and stronger economic prosperity due to middle-class expansion in most developing economies would increase the demand for energy by an additional 25% (OPEC, 2017). The OPEC (2017) further projected that global consumption will rise to 102.3m b/d in the interim (2022) up to 1.7m b/d to 111.1m b/d by 2040 and in the longer term. More so, industrialisation of the BRICs economies, demand for road transportation and movement of goods and services and urbanisation in Africa could pave the way for more demand for both natural gas and crude oil (BP, 2018).

Furthermore, there are economies such as Russia, Saudi Arabia, Ghana, Nigeria, Venezuela, etc. that thrives on the exportation of fossil energy. According to the Federal Bureau of Statistics and research, 90% of Nigeria's government revenue and 40% of GDP comes from crude oil/gas export (Tami and Moses, 2015; Sanusi, 2010). Accordingly, there has been a huge investment in the protection of crude oil and gas installations predominantly located in the Niger Delta. It is reported that Shell Petroleum Development Company (SPDC) spent $383 million USD (40% of its security budget and expenditure) in protecting critical oil and gas installations in the Niger Delta. This is in addition to the annual $103 million USD government contract on the protection of oil installations and maritime safety in the region.

It is observed that most of these huge expenditures are on social risks and volatility of the Niger Delta due to agitations from aggrieved communities. It is argued that the impact of climate change could trigger more catastrophic threats on critical oil and gas installations in the region as more coastal areas across the globe becomes vulnerable (Feng et al., 2018; Shen, Feng and Peng, 2016; Denner et al., 2015). Though renewable energy investment is expected to thrive in Africa and Nigeria market, how would perennial bureaucratic bottlenecks and lack of legislative framework, political tussle and the Nigerian business mindset, impact on smooth growth? With this background and in a business as usual scenario, crude oil and gas exploration and production stand a chance of forming the backbone of continued economic growth and prosperity in Nigeria and other similar countries. It would, however, attract foreign direct investments and may later pave the economic strength for investments in renewable alternatives. These arguments suggest that the oil and gas industry would maintain high significance into the future energy demand and supply and would continue to support economic growth across the global south.

Ultimately, this implies that impact of climate change related disasters such as storms surges, flood, and sea level rise and intrusion on oil and gas infrastructures could outdo economic growth plans with severe cascading consequences on other sectors of the economy. These consequences interfere with economic growth rates and exacerbate poverty, food shortages, water scarcity and poor health conditions of the people. These arguments justify the choice of assessing the vulnerability of critical oil and gas industry in this study in the context of the Niger Delta. The rationale is to provide insight into the need for adaptation investment in the industry aimed at creating asset resilience and resistance needed to sustain economic development in Nigeria.

2.2.1 Oil and Gas Infrastructures in the Niger Delta

Literature scoping has revealed some oil and gas infrastructures which could be assessed for criticality and vulnerability. Field exploration and stakeholder’s engagement in this study further capture and illuminate more infrastructures for prioritisation based on criticality and vulnerability.

Table 1; List of selected oil and gas infrastructure in the Niger Delta

S/N	Infrastructure
1	Well-Head
2	Terminals (oil and Gas)
3	LNG Bonny Terminal
4	Trunk lines (12”-30”)
5	Flow Stations
6	Flow lines
7	Loading Bays
8	Transformers/High Voltage cables
9	Storage Tanks
10	Roads
11	Bridges
12	Allied Assets – residential & reserves

These infrastructures are spread across upstream, downstream and midstream sector forming the central systems for this study.

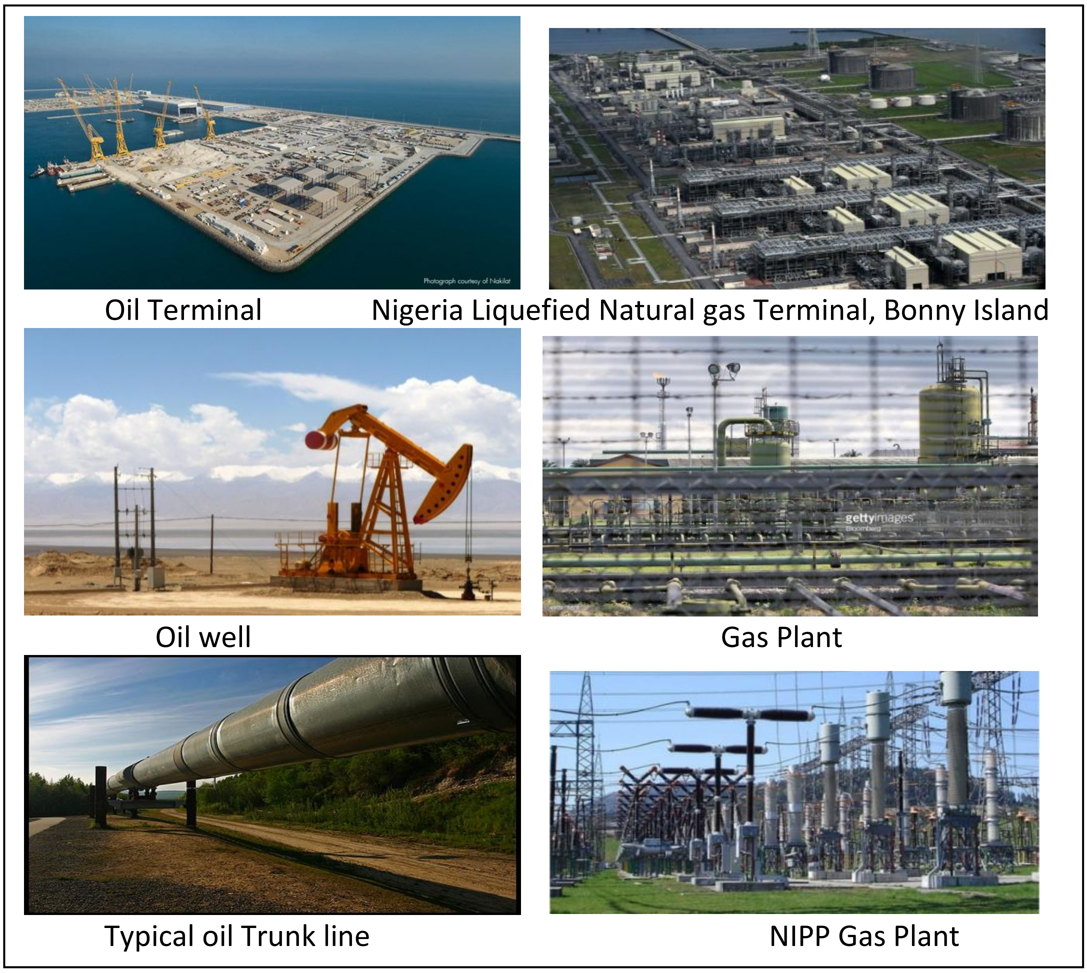

Figure 9; the major oil and gas infrastructures in the Niger Delta

2.4 Systematic Literature Review

2.4.1 Introduction

To conduct a valid criticality and vulnerability analysis of selected infrastructure by applying a multi-criteria based analytic hierarchy process (AHP), a systematic literature review is adapted to illuminate the relevant criteria or indicators that have been applied in the vulnerability assessment of climate change impacts from a global perspective. A systematic and analytic literature review has been applied by researchers in identifying salient themes, vulnerability criteria and indicators and applied in the identification of research gaps (Jamali and Karam, 2018b; Maleki et al., 2018; Sebesvari et al., 2016; Brereton et al., 2007). Specifically, vulnerability assessments in deltas undertaken by other researchers have identified numerous criteria that are hybridised with indicator-based methodologies in underpinning in social, ecological and system exposed to threats (Sebesvari et al., 2016). Criteria are important in this study as it aims to explicitly capture how environmental, social, and engineering thresholds of infrastructures could be vulnerable to climate change impacts in the oil and gas industry. Identified criteria are further synthesised through the application of AHP to determine each criterion weight and applied as instruments for prioritising selected infrastructure for criticality and vulnerability. It is believed that synthesising the criteria with AHP could indicate their weight and produce tailored sub-criteria for criticality and vulnerability assessment. It paved the way for the construction of critical arguments on indicators of the Niger Delta vulnerability.

2.4.2 Systematic review methodology and outcome

To understand and scope the criteria that have been conceptualised in vulnerability assessments, a systematic review process was adopted. A systematic review is a technical approach that summarises existing themes, criteria or indicator, methodologies, etc. through a refined review strategy using the inclusion and exclusion of specific indices. In this review, keywords are carefully scoped from highly referenced publications and reports on climate change and environmental studies (Watson and Albritton, 2001; McSweeney et al., 2010; IPCC, 2014; OECD, 2017) and applied in SCOPUS database. Scopus is argued to contain a comprehensive database of peer-reviewed journal articles across environmental and ecological sciences, social sciences and the built environment where vulnerability assessments are focused (Shukla, Sachdeva and Joshi, 2018; Landauer, Juhola and Söderholm, 2015). Searching a single robust database is a theoretical strategy for eliminating the stress of sorting duplicated journals arising from multiple databases as opposed to the approach of (Shukla, Sachdeva and Joshi, 2018). Keywords from generic scoping of IPCC and other experts theories were identified for the search and included in the following order *“vulnerability assessment” OR “climate impact assessment” OR “vulnerability indicators” OR “susceptibility indicators” OR “vulnerable infrastructure” OR “adaptation assessment” OR “variability indicators” OR “climate impact indicators” AND “critical infrastructure” OR “sensitive systems” OR “coastal infrastructure” OR “criticality assessment” OR “critical infrastructure.”* The search resulted in 202 articles. Constructed boundaries included peer-reviewed articles published in the English language between 2008 and 2017 (figure 11) in Engineering, Environmental Sciences, Earth and Planetary Sciences, Social Sciences, Energy and Multidisciplinary (figure 12). 128 peer-reviewed journal articles were filtered excluding conference papers, books and book chapters, editorials and surveys.

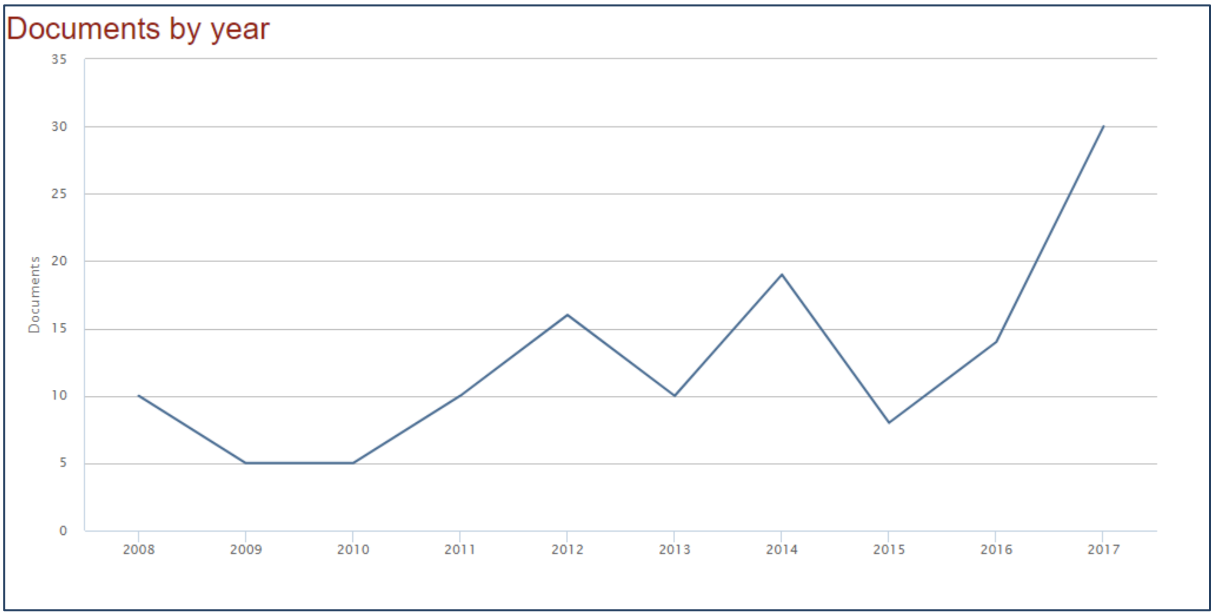

Figure 10; Source of peer-reviewed articles by year

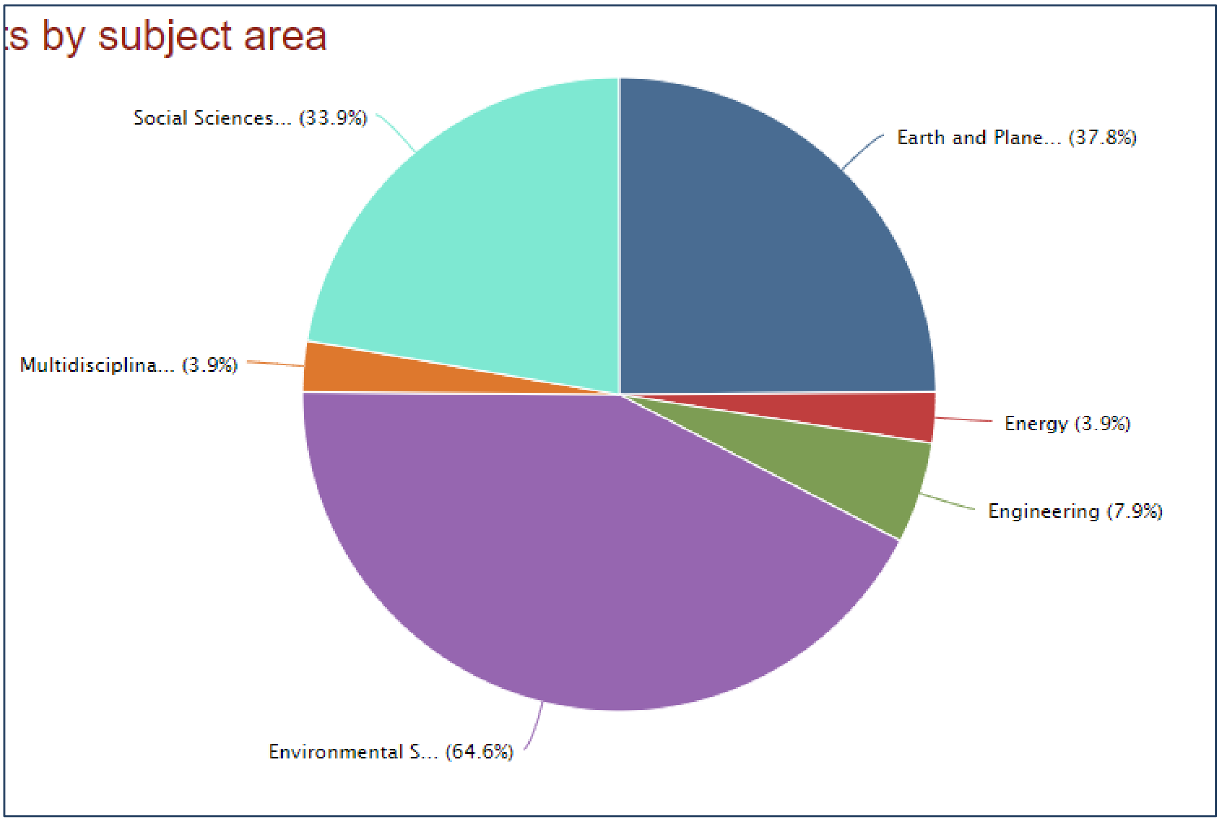

Figure 11; Obtained peer-reviewed articles by subject areas and year of publication

This boundary of delineation was constructed in line with the study focus on built systems in the selected subject areas to underpin the criteria that have been applied in scholarly activities on vulnerability and criticality assessment within the past decade.

However, the result shows that 64.6% of a decade of scholarly activities on vulnerability assessment is from environmental science while 37.8% and 33.9% arises from Earth and Planetary Sciences and Social sciences respectively. This is expected because the impact of climate change (flood, drought, etc.) is ultimately on the environment and interdependent burdens on built systems especially in coastal areas and could have attracted research attention (Cabral et al., 2017; Semedo et al., 2016). The intensity of vulnerability research since 2015 is probably because of the corresponding frequency of extreme climate change actions such as global flood, hurricanes, and temperature events and the aftermath of the 2015 Paris (COP 21) agreement. Though the Paris agreement tends to focus more on mitigation and sustainability, it has also provoked actions on critical adaptation planning and investment across industries facilitated by the scholarly investigation.

2.4.3 Review of Vulnerability and criticality indicators

128 articles were exported in MS spreadsheet for further review and analysis. 53 (41.4%) of articles with a focus on "vulnerability" and "criticality" from abstracts and title synthesis were identified. In a separate worksheet (see appendix XXIX), the 53 papers were reviewed individually according to the following sub-themes: year of publication, study design, number of citations, keywords, study focus, indicators/criteria used, paper type and source. Some of the relevant sub-themes and statistical analysis are presented in *Table 2*.

Table 2; Analysis of generated sub-themes

Year of Publication	Study Design			Number of Papers (%)	Average Citations (%)
	Qualitative	Quantitative	Mix		
2008 and 2009	3	0	1	7.5	13.8 (423)
2010 and 2011	6	2	3	20.8	59.0 (1,812)
2012 and 2013	4	1	2	13.2	12.2 (374)
2014 and 2015	8	2	2	22.6	12.5 (384)
2016 and 2017	11	6	2	35.9	2.5 (76)
TOTAL	32	11	10	53	3069

From the table, 32 (60%) of scholarly peer-reviewed vulnerability assessment study designs applied qualitative approaches against 20% each for quantitative and mixed methodologies. This is because most recent studies are sustainability driven, focusing on how climate change and environmental disaster could impact on socio-economics, human health, and environmental elements. Sustainability research is critical in climate change debates as indicated in the review (Chappells and Shove, 2005; Eriksen et al., 2011). However, this indicates an existing gap in the application of mix and quantitative methodologies in investigating vulnerability and criticality of infrastructures between 2008 and 2017 globally. Hence, this study adopts a mix method approach as part of the contribution to closing the disparity between qualitative and quantitative or mix methods studies in vulnerability assessment in the context of climate change in the Niger Delta perspective.

2.4.4 Identified criteria

To identify the criteria available from 53 peer-reviewed articles based on vulnerability and criticality domains, further synthesis was conducted by colour coding the indicators in an excel spreadsheet. Criteria arising from sustainability-based assessments (environment and ecosystems, human health, income and financial implications etc.) were coded pink and classed as ***criticality criteria*** domain while built systems-based assessments (energy, transport, telecommunication, roads infrastructures etc.) were coded green and classed as ***vulnerability criteria*** domain (table 3). Each domain was manually counted; 56.6% arises from criticality domain against 43.4% that focuses on vulnerability domain. Each domain criterion was aggregated under vulnerability and criticality and analysed using Microsoft word cloud to highlight dominant criteria according to their frequency in each domain (see *Figure 12* and *Figure 13*)

Table 3; Identified Criteria for Vulnerability and Criticality Assessment

Vulnerability criteria (43.4%)		Criticality criteria (56.6%)	
Literature Indicators	**Themed Criteria**	**Literature Indicators**	**Themed Criteria**
Exposure, Sensitivity, Adaptive capacity, Potential impacts, Adaptation, vulnerability, Network, Criticality, adaptive capacity, stability, Extreme weather, surface elevation, Hybridisation of indicators on proximity, sensitivity, adaptive capacity in assessment, exposure to risk,, Capacity, local conditions, exposure, sensitivity, social factors, adaptive capacity, linkages, Climate exposure, impact, sensitivity, and adaptive capacity, vulnerable (Interdependencies), elevation, deficiencies in infrastructure make people s more socially vulnerable, relevant Exposure, nearness to offshore and coastal systems, Changes in structure, and use of Maps, flood magnitudes, low lying lands, distance to shore, Adaptation capacities of institutions, integration of systems, concepts of exposure, susceptibility and resilience, network nodes of systems, Sensitivities and priority, and common linkages and problems, Adaptation capacities, vulnerability range, complexity of infrastructure, strengths and weaknesses, adaptive capacities, distant to vulnerable areas	*Exposure* *Sensitivity or criticality* *Adaptive capacity* *Age of infrastructure* *Presence of risk or burdens* *Proximity* *Interdependency* *Risk level*	independent, correlated, cascading, exposure, collaborations among different expertise, Economics, Environment, expenditure, Living pattern and prevention performance, Population density, include social, economic, and human health ecosystem health and the integration of ecological systems with economic implications, social and human health factors, constraints of time, resources, Human capacity, Interlinked and supporting infrastructure, ecosystems for human well-being, Human dependence, Ecosystem influence, Human wellbeing, ecosystem services and human well-being, social systems, complex infrastructure, Social threats, potential menace, Regulations and environmental awareness, level of strains, Economic, Environmental factors, Social, Economic, Environmental, Physical adaptations, human practises, sustainability, socio-cultural carrying capacity, vulnerability assessment use social, economic, cultural, institutional, environmental, and physical, socio-economic factors, very high fragility, physical, environmental and socio-economic, Pressure Index and Fragility/sensitivity, cost, an ecological, social-ecological, sensitivity indicators, monetary impact, socioeconomic indicators, environmental, poverty, human health, key economic sectors and services, human security, and urban areas, age structure, human health, income communities, exposure, socio-economic development, physio-chemical and biological parameters, biodiversity, ecosystems and economies and human health, Human elements, environment system, uncertainty, Historical records of burden, Age and type of building, cost of repair and Building sensitivity, ecosystems concern or communities	*Interdependence* *Economic factors* *Environmental concerns* *Engineering ability* *Cost of maintenance* *Cost of Replacement* *Societal issues* *Human Health* *Human safety* *Ecosystem effects* *Physical Alternative systems*

Figure 12; Themed criteria from literature indicators for vulnerability assessment

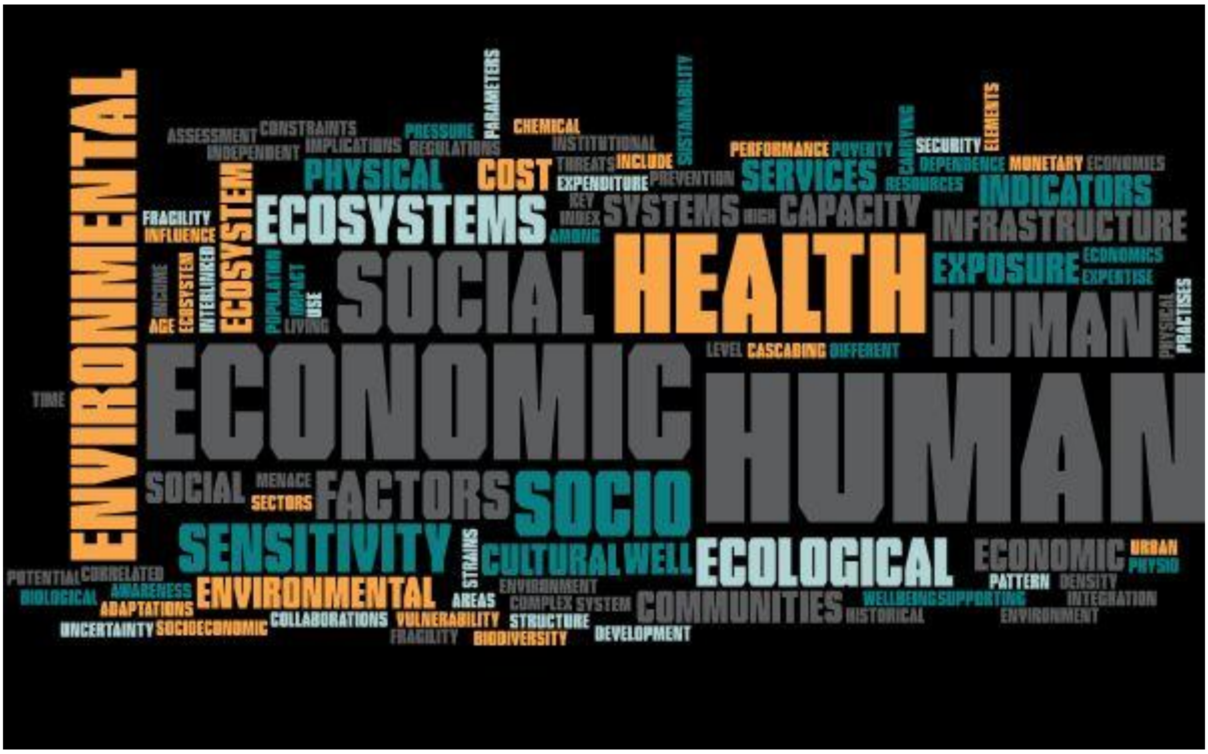

Figure 13; Themed criteria from literature indicators for criticality assessment

The dominant "themed criteria" reflected in *Figure 12* are *Figure 13* and summarised and applied as principal indicators or criteria for evaluating the vulnerability and criticality of oil and gas infrastructure to climate change impacts (Maleki et al., 2018). However, criticality and vulnerability criteria are selected and regrouped based on themes frequency arising from reviewed papers. See table 4 below.

Table 4; Reviewed criteria for evaluation of vulnerability and criticality of infrastructure

Vulnerability Criteria	Criticality Criteria
1) Presence of climate burdens	1) Economic niche
2) Exposure to systems	2) Societal relevance
3) Criticality	3) Environmental concern and
4) Proximity to risks	4) Interdependence
5) Adaptive capacity	
6) Age of infrastructures	
7) Interdependence	

2.5 Synoptic Review of Vulnerability Assessment Criteria

Limiting the criteria to seven (7) most frequent outcomes for the vulnerability is structured to reduce the ambiguity of the analysis, maintain a manageable size of evaluation within the time frame and as suggested for studies involving analytic Hierarchy Process (AHP) (Goepel, 2013b; Fekete, 2011a; Saaty, 2003). Nonetheless, the following sections present a brief description of each criterion and demonstrate how the criticality criteria are further decomposed into the maximum criteria (7) of evaluation.

2.5.1 Presence of Burden(s)

Because infrastructures are vulnerable to prevailing risks/burdens, one crucial criterion for impact assessment emerging from the review is the presence of climate risks or burdens in each location. It considers sources of climate risk(s) that an asset could be vulnerable to. Though it is difficult to argue that infrastructure in a built environment is completely out of climate risks, there is a tendency that for given climate risk, a system may not be vulnerable if there are no burdens (Adelekan, 2010; Boisvenue and Running, 2006). For example, oil/gas infrastructures in the Niger Delta could not be vulnerable to hurricane or cyclones because these risks are no prominent in the region. Therefore, the presence of climate hazards sources is the basis of vulnerability assessment and these risks can be quantified to determine the magnitude upon which surrounding infrastructures could be susceptible. Existence and frequency of climate risks further widened the susceptibility levels of infrastructures (Denner et al., 2015).

2.5.2 Exposure

As infrastructures continue to be forced by climate extremes, one of the operational measures needed to quantitatively assess vulnerability is exposure (Jenelius, Petersen and Mattsson, 2006). Exposure is the measure of the susceptibility of infrastructure to climate risks. Literally, systems located around the coastal area or within river banks are more exposed to storms and flooding than those buried in a desert environment. Similarly, systems located in low elevation areas are likely to be at risk of silting and flooding when sea level rises. Buried Pipelines that runs through floodable rivers and erosion-prone areas are exposed as much as those that run on bare earth, which are exposed to extreme temperatures, flood, and storms (Sano et al., 2015). Sub-elements of exposure include inundation, floodable coasts/planes and stormy pathways, and high temperature that render systems vulnerable (Bhuiyan, Md Jabed Abdul Naser and Dutta, 2012; V. R. Burkett et al., 2008; Chappin and van der Lei, 2014).

2.5.3 Criticality

Growing environmental change and social factors such as terrorism have caused some infrastructures in energy, telecommunication, financial, civil administration, chemical industries to be classified as critical (Alcaraz and Zeadally, 2015). Though it is argued that the criticality or sensitivity of infrastructure varies according to perceptions, the most investigated from the literature review are energy, telecom and transport systems (Varianou Mikellidou et al., 2017a; Pursiainen, 2017; J. Moteff and Parfomak, 2004a). The criticality of systems may depend on the sensitivity of infrastructures based on its revenue base, the sensitivity of the surrounding environment (ecosystems, freshwater, etc) that sustained the economy. For example, an oil well located in social environments such as marketplaces in the Niger Delta could be considered as critical due to impacts it may generate if disrupted by flood (Alcaraz and Zeadally, 2015). A critical asset is, therefore, any given system (physical or cyber) that is so vital to an economy, organisation or agencies; which its destruction could cause enormous impact in economic plans, policies, security, lives and health of the population (Moteff, 2010; Zimmerman, 2006).

2.5.4 Proximity

The concept of proximity is one of the physical parameters in vulnerability assessment which occurred in the systematic review for climate impact assessments (Espada, Apan and

McDougall, 2017; Denner et al., 2015; Correa and Yusta, 2014; Arboleda et al., 2009). Generally, proximity to risk factors is considered in infrastructure installation and building. However, most theories failed to capture the importance of proximity in climate impact assessments. Denner et al. (2015) assessed the Loughor Estuary shoreline using physical parameters to determine vulnerabilities of systems in a coastal area of Wales. They argued that significant infrastructures ranging from energy systems, residential, transport, etc. were most vulnerable due to their proximity to the seashore. Their findings corroborate other investigations by Mejia-Dorantes, Paez and Vassallo (2012) who further justified proximity as a physical indicator for vulnerability assessment. Proximity helps in estimating the possible magnitude of impacts and provide indices for decision making and planning in climate impact assessment (Wamsler, Brink and Rivera, 2013). It is therefore important to consider location as a possible means by which an asset may be susceptible to climate risks. Hsieh, Tai and Lee (2014) argued that the closer a system is to a source of climate risks (e.g coastal area), the more vulnerable it would be when impacts (such as tides and storms) are discharged.

2.5.5 Adaptive Capacity

Adaptive capacity is the measure of infrastructures' ability to withstand or adjust to accommodate extreme environmental impacts. Infrastructures are expected to have a level of resilience and resistance to environmental burdens when exposed (Zio and Golea, 2012). This implies that though infrastructures may be exposed but could possess the ability to withstand impacts. A system with maximum and equal adaptive capacity (resilience and resistance) to a given risk magnitude is described as less vulnerable (Engle, 2011). Adaptive capacity can also be seen from an administrative perspective as the preparedness of organisational management to develop resilient policy frameworks-based adaptation for the protection of infrastructures. If a critical vulnerable infrastructure has a weak adaptive capacity, it is highly susceptible to climate impacts but organisational policies such as annual climate assessments could provide the required resilience (Jenelius, Petersen and Mattsson, 2006).

2.5.6 Age and Infrastructure life cycle

The phenomenon of ageing or obsolescence of infrastructure is crucial in the oil/gas industry globally as thousands of assets designed to last decades are fast becoming obsolete necessitating prompt upgrade and decommissioning due to extreme climate events (Karl, 2009). The rates of climate change events and corresponding impacts seem to exacerbate ageing and weaknesses associated with sensitive systems. Shen, Feng and Peng (2016) used age as an appraisal factor for prioritising infrastructure due to their vulnerability to security and environmental hazards and suggested rehabilitation and reconstruction to optimise performance. They argued that the age of infrastructures could aggravate impacts on linked systems with weak adaptive capacities. The combine weaknesses due to age and obsolescence could exacerbate assets vulnerability to environmental threats. Climate change risks such as flood, temperatures and storms have the capacity to override and compromise resistance and resilience associated with aged infrastructure. Zimmerman (2004a) further argued, "Infrastructures that are in poor condition due to age can be more vulnerable to such environmental intrusions." He contended that knowledge of how infrastructures resilience is challenged by extreme events through vulnerability assessment is crucial in managing infrastructures. This study builds on these propositions to conduct this vulnerability assessment on critical infrastructure with the view of suggesting the adaptation measures that could be implemented for oil and gas infrastructure protection.

2.5.7 Interdependent Infrastructure

Interdependence or interlinkages of systems has been emphasised in the vulnerability assessments globally in subjects outside climate change vulnerability studies (Correa and Yusta, 2014; Espada, Apan and McDougall, 2015). Interdependence is a crucial criterion for vulnerability assessment in this study because the streams in oil and gas industry are highly interlinked such that impact from one stream often cascades through to others within the value chain as indicated in ***Figure 14***.

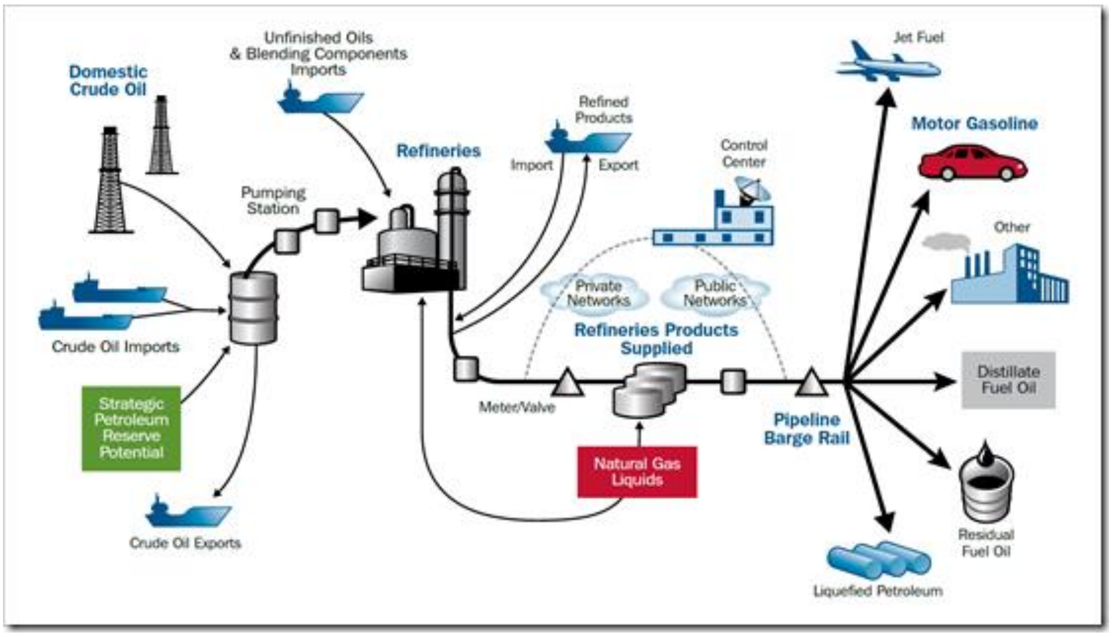

Figure 14; illustrates the interdependence of energy infrastructures. Source: Dixon (2010)

Due to these interdependencies and linkages, vulnerability assessment could incorporate pragmatic control systems that reduce cascading transmission of climate-induced impacts such as floods, wind storms, etc. in the Niger Delta context. Applying interdependence in assessing vulnerabilities is strategic for spatial systems assessments in the industry. Highly interlinked industries are more likely to be severely impacted than less linked systems (Garg, Naswa and Shukla, 2014). However, most infrastructures are dependent upon each other for effective service delivery; for example, electrical systems are connected to transport, water, telecommunication, tourism, residential and commerce systems (Wang, Jiang and Lang, 2017; Wang, Ma and Li, 2011). Wang, Hong and Chen (2012a) argued that interdependence is a crucial criterion for vulnerability analysis.

2.6 Synoptic Review of Criticality Assessment Criteria

This section presents synoptic reviews of criteria for criticality assessment following from the systematic review. As discussed earlier, the criticality of infrastructure is its sensitivity and essential niche in society. Some authors argued that critical infrastructures support national security, energy supply, economic, health, and general sustainable ambient of economies such that their failure could pose severe consequences on sustainable development (Alcaraz and Zeadally, 2015; Moteff, 2010; Moteff and Parfomak, 2004a; Egan, 2007). In line with these arguments, the Niger Delta oil and gas infrastructure are classed as critical systems because they form the bedrock of Economic development and planning in Nigeria and serve as an energy hub for other global economies.

However, to investigate the criticality of oil and gas infrastructures, four (4) criticality criteria are further decomposed. Accordingly, it is contended that effective criticality assessment considers the cost of system repairs and financial implication of impact on the society, risk on human life and ecosystems, cascading effects, and mitigation - availability and affordability of adaptation measures (Landauer, Juhola and Söderholm, 2015; Correa-Henao and Yusta-Loyo, 2015; Arboleda et al., 2009; Chappells and Shove, 2005). In view of this, the criteria for criticality evaluation are decomposed to capture all elements of criticality as shown in table 4b and also *Figure 15*.

Table 4b showing principal and decomposed critical assessment criteria

Principal Criteria	**Decomposed Criteria**
Economic Niche	i. Replacement value ii. Economic/societal relevance
Environmental concerns	iii. Impact on Human Health/safety iv. Impact on natural ecosystem due to failure
Engineering capacity	v. Available alternative(s) vi. Affordability of Alternative(s)
Interdependence or interconnectivity	vii. Interdependence or interconnectivity*

Analytic hierarchy process (AHP) principle also requires thorough synthesis of criteria to ensure that intangible criteria are captured and constructed as standalone criteria in the multi-criteria analysis (Armenakis and Nirupama, 2013; Yousefpour et al., 2012; Yu, 2002). The criteria are briefly defined in subsections 2.5.1 to 2.5.4.

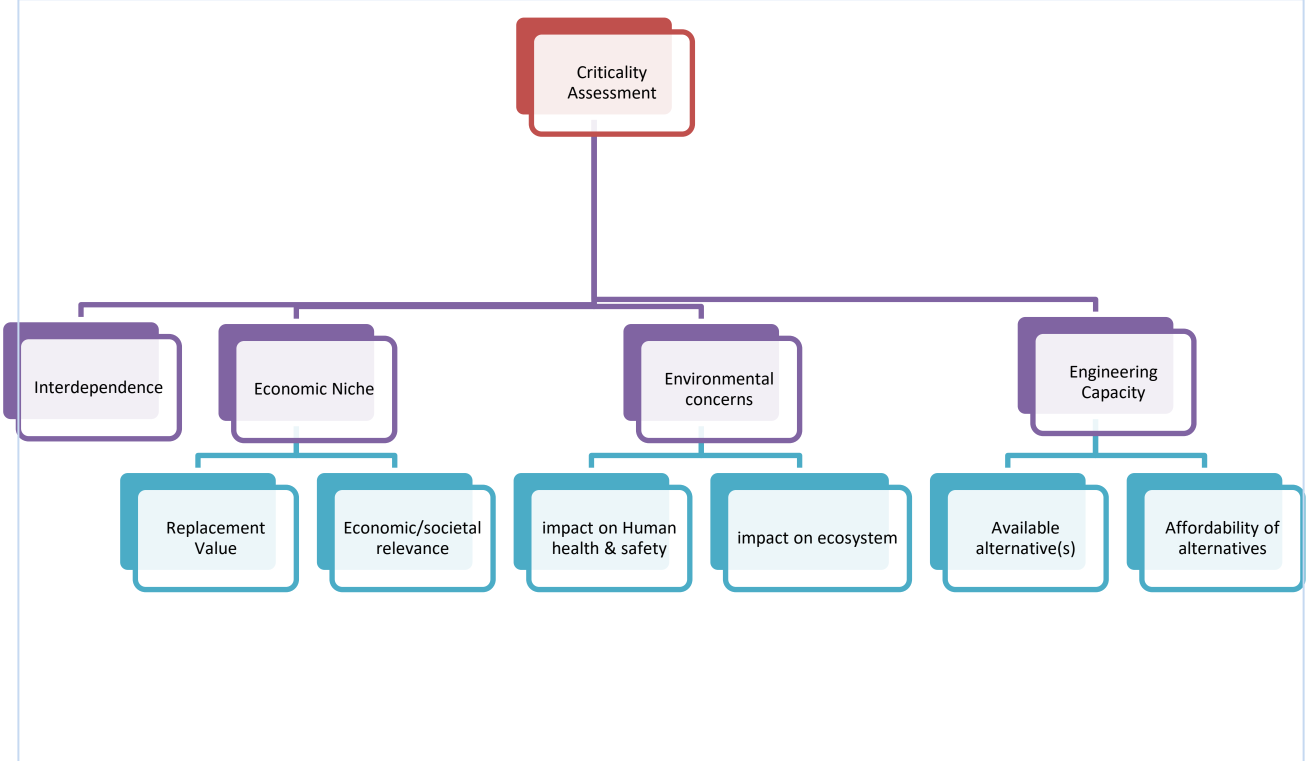

Figure 15; a Hierarchic array of a criticality assessment framework for AHP use

2.6.1 Interdependence

The conception that national critical infrastructures are extremely interconnected and jointly dependent in complex ways (physically or virtually) such as expressed in telecommunications, transport and energy is critical for vulnerability assessment (Rinaldi, Peerenboom and Kelly, 2001a). Interdependence reflects in both domains of assessment in this study and has been discussed in on page 38.

2.6.2 Economic Niche

Building large and interdependent infrastructures involves significant investment through capital and operational expenditures usually from shareholders in joint ventures or public funds. These huge investments are embarked with the perception that the assets contribute to global GDP growth and sustain economic planning (Del Bo, Karabacak, Ozkan Yildirim and Baykal, 2016). Nigeria infrastructures investments are largely in the oil and gas sector; located in the coastal Niger Delta. Though most of the oil/gas assets in the Niger Delta are jointly operated under (JVCs), the government seems to be the major shareholder of consequences of flood and other related impacts on the systems. Hence, oil and gas systems occupy a critical economic niche in Nigeria. They range from extremely large, complicated to less complicated but highly sensitive systems. Economic Niche is seen through the lens of 'societal relevance' and the ‘financial burden’ of replacing affected systems. This sub-criteria are discussed independently in the following sections:

2.5.2.1 Societal Relevance

Societal relevance underpins the value of royalties and economic benefits generated because of the presence of infrastructure in a city, community or state. In the Niger Delta, strong hospitality businesses, commercial activities such as banking services, markets, educational, social amenities, and towns are usually built around oil and gas infrastructures (Huang, Liou and Chuang, 2014). This is because these systems such as the Eleme Petrochemical terminals, Bonnie NLNG, attract foreign experts and demands for services with a corresponding capital inflow that boost local commerce for local economic development. Residents rely on the viability of local services for daily income and could be devastated if these systems are impacted by climate extreme events. Due to this high relevance of infrastructure to local economies, ‘*societal relevance’* is argued as a considerable criterion for criticality assessment.

Furthermore, the revenue from crude oil and gas is highly significant in national budgeting and spending (Ariweriokuma, 2008). It is argued that since late 2015, Africa’s largest oil producer has been struggling economically due to the fall in crude prices. In this study, the emphasis is on the relevance of crude oil revenue and its relevance in sustaining both local and national economies, hence making the societal relevance of ‘economic niche’ a vital factor for criticality assessment. Infrastructure supports all form of revenue from the sector.

2.5.2.2 Replacement Cost

In assessing and managing critical infrastructures severely impacted due to weak adaptive capacities, design failure or obsolescence, the cost of replacement is usually prohibitive. Replacement cost is the estimated financial implications for replacing parts or whole infrastructure. Cost implications are usually central aspects of an organisation’s planning to avoid high insurance premium (Hinkel et al., 2014). In the oil and gas industry, corporate social responsibility has been stretched by the impact of flood and another disaster on communities. The cost of evacuation and resettlement of communities are included as part of replacement cost in flood accounting; hence form a critical criterion for measuring the criticality of infrastructures.

2.6.3 Environmental Concerns

The concerns resulting from the impact of climate change on ecosystems and sustainable development is given a wide consideration in the literature involving criticality assessment. Secondly, human existence as part of the environment further necessitates a high level of sensitivity in discussing climate burdens in addition to the multiple negative threats on biodiversity, air quality, fresh and groundwater, and scarce resources (Jiricka et al., 2016; Hitz and Smith, 2004; Jones, 2001a). Environmental concern emerges as criticality criterion because of the combined potential impact of climate change on human health and safety and consequences on fragile ecosystems, as briefly described in the following sections.

2.6.3.1 Impact on Health and Safety

Disastrous infrastructure failures have been continually associated with the oil and gas industry over time. The April 2010 Macondo blowout (popularly known as the Deepwater Horizon oil spill) created a historical case associated with infrastructure failure in the oil and gas industry and severe impact on both human wellbeing and the ecosystem. It left eleven (11) BP staff death and contaminated marine ecosystems more than any oil spill on record (Smith et al., 2013; Egbchue, 2012). The inclusion of *'impact on human health and safety'* as criteria for criticality assessment by other researchers could arise from the history of infrastructure failure and the current impacts of climate change burdens such as flood, extreme temperatures, heavy downpour and storms on human existence. More so, natural hazards such as earthquakes, extreme snow, ice, hurricanes volcanic actions, wildfires and landslides; have constantly forced infrastructure failure all over the world resulting in an unprecedented impact on the Health and Safety of lives and property (Hardoy and Satterthwaite, 2014; Hemingway and Priestley, 2014). In the Niger Delta, human-induced infrastructure disruptions had adversely affected human health and safety. The vulnerability of infrastructures to climate change could further widen the chances of severe consequences on human health and safety in the region, hence the inclusion of this criterion in the criticality assessment.

2.5.3.2 Impact on ecosystem

The April 2010 Macondo incident quoted earlier is said to have a severe impact on the ecosystem. Continual crude oil spill estimated at 4.9 million barrels for eighty-seven (87) days was recorded (Smith et al., 2013) - thrice the average daily production capacity during May - September 2016 of the entire Niger Delta. The continual gushing of 4.9 million barrels of crude oil severely impacts the natural ocean ecosystem leading to the death of phytoplankton, seabirds, fish, corals and the entire aquatic food chain and food web (Joye, Teske and Kostka, 2014). Aside from the immediate impact, as the oil continues to spread hundreds of kilometres, cascading impact on affected sea animals, causing long-term diseases and physiological abnormalities (McAndrews, 2011). This argument justifies ecosystems as sensitive and critical and becomes a criterion for criticality assessment of climate change impact on oil and gas infrastructure in the Niger Delta context. Nonetheless, climate change impact on the ecosystem could potentially and indirectly affect oil/gas infrastructures significantly and pose environmental consequences on endangered species and hamper population growth for the microbial community (Joye, Teske and Kostka, 2014).

2.6.4 Engineering capacity

Oil and gas companies, national governments and policymakers could continue to face tough and challenging decision-making in planning, designing, and management of critical infrastructures especially as extreme climate-related burdens become prevalent (Strantzali and Aravossis, 2016; Willows et al., 2003). Understanding the frequency, magnitude and uncertainties associated with climate burdens further puzzled engineers and make engineering capacity of infrastructures a good construct for criticality assessment in this study. However, to properly construct the argument for criticality assessment of infrastructures, there is a need to understand how alternative systems could be useful when conventional systems are overwhelmed. Therefore, the availability of these alternatives could be considered for evaluating criticality. In managing assets, the budget is often made by practitioners and experts and counted as a marginal cost in climate (flood, storms, etc.) accounting in the industry (Emily Rowan et al., 2013). This implies that in addition to the availability of alternatives, cost evaluation is essential in criticality analysis. Francis and Bekera, (2014); Brooks, Adger and Kelly (2005) argued that 'availability' and 'cost' of alternative engineered capacities are captured for assessing the operations of machines to elicit their criticality. Availability and cost of alternatives are briefly described in the next sections to indicate how they fit into criticality evaluation in this study.

2.5.4.1 Availability of Alternatives

This seeks to investigate the preparedness and readiness of organisations with additionally available logistics to support infrastructure in case of any failure; forced by either human or by natural hazards (Smith et al., 2009; Füssel and Klein, 2006). In recent times, analysis of infrastructure performance and future capabilities has taken a new dimension. Decoupling to reduce GHG emission and investments in parallel systems to form alternative systems have been suggested for adaptation purpose (Kennedy and Corfee-Morlot, 2013). Infrastructure with operational alternatives is less likely to pose significant threats to organisations as compared with those operating through a pipeline approach. To resist or reduce climate impacts on systems, alternative systems are expected to be installed to reinforce operational capacity. Nonetheless, infrastructures with little or no alternative support systems and adjudged as critical could be by extension vulnerable to climate risks. Therefore, should receive much attention from assets managers to ensure that all adjustments, repairs, and routine maintenance are carried out at the appropriate time. Oil and gas systems in the Niger Delta were installed when global climate change was not a critical environmental issue. This implies that alternative approaches were less considered despite the criticality and sensitivity of the industry (Bai and Bai, 2012; Ranger, Reeder and Lowe, 2013; Wilbanks and Fernandez, 2014). With recent events, it has become imperative to recount the availability of alternative in evaluating the criticality of oil/gas assets in the Niger Delta context to ensure that adaptation measures are effective sustainable and encompassing.

2.7.4.2 Cost of Alternatives

One option is to establish that there are available alternatives, and another is to critique the affordability of alternatives. The cost of design, fabrication, construction, installation and operation of oil and gas infrastructures is a critical factor in the oil industry. The cost of an alternative in this study is the estimate of the economic value of substitute infrastructure under climate impacts. The cost required to adapt to climate change by substituting an infrastructure apparently could intensify the criticality of assets (Verma et al., 2017; Moteff and Parfomak, 2004a). Emphatically, there are different phases of oil and gas equipment design, construction, installation, operation and routine maintenance. Each of these phases involves huge capital expenditure depending on infrastructure purpose, size, operational environment, design complexity, prevailing economic situation and regulatory framework (Karabacak, Ozkan Yildirim and Baykal, 2016).

There are a few examples of capital-intensive infrastructure in the oil and gas industry that could have severe alternative cost implications for the industry if impacted by climate change disasters:

- Van Den Broek Et Al (2010) argued that investment in large-scale carbon capture and storage infrastructure of "600 km of CO_2 trunk line" expected before 2020 is estimated at 720 million and 340 million Euros; in the Netherlands.
- Pipelines infrastructure constitutes a high invest across oceans, seas, rivers and covers long distances (Sklavounos and Rigas, 2006; Karamitros, Bouckovalas and Kouretzis, 2007). The Langele pipeline connecting Norway and England covers 1,200 km and cost $3.3 million USD to construct.
- The world longest oil pipeline – Druzhba, also known as the "friendship pipeline" extending from Russia, covers over 4,000 km and cost about $12.7 million USD. Its extensions of about 1,800 Km attract an extra $2.5 million USD (Grigorieva and Grigoriev, 2007).
- In Africa, construction of the West African Gas Pipeline (WAGP) between 1982 and 2009 covers 678 km at a cost of $974 million USD; extending from the Niger Delta towards other west African countries. A recent report by the Guardian (2015) suggests that about 12,700 km of pipelines worth $14bn USD were vandalised in addition to the devastation and the spill that attracts an extra cost of remediation.

From the examples above, though constructed some decades ago, the investment cost surpasses annual budget of some African countries. More so, the present financial crises and inundating crude oil prices could further challenge the replacement of critical systems. Hence, the cost of the alternative is a crucial indicator of the criticality assessment adopted for this study.

2.7 Chapter Summary

This chapter reviewed the phenomenon of climate change; its causes, impacts, projections and cost of inactions, to indicate the gaps in literature and opportunities for contributions from this study. It adopts a systematic literature review to further illuminate the gaps and present the criteria for criticality and vulnerability assessment of oil and gas infrastructures in the Niger Delta context. Accordingly, 128 papers that focus on vulnerability assessments were filtered from the Scopus database with selected keywords and further restricted to 53 peer-reviewed journals published in the English language. Three of four major criteria (economic niche, environmental concerns and engineering capacity; from the review are further decomposed into; societal relevance, replacement cost, impacts on human health and safety, impact on ecosystems, availability and cost of alternatives. Decomposition resulted in the even (7) criteria in addition to 'interdependence'; for criticality assessment. Similarly, seven (7) criteria; including exposure, the age of infrastructure, the presence of burdens, interdependence, adaptive capacity, proximity, and criticality, are synthesis from the papers and analysed for assessing the vulnerability of critical infrastructures in the Niger Delta.

CHAPTER THREE

RESEARCH FRAMEWORK

3.1 Introduction

This study involves scoping information on vulnerability assessment procedure, infrastructure selection, and operationalising (mainstreaming) outcome, hence the need for an empirical framework that forms the driving background of overall research approach. It is argued that a framework for vulnerability assessment should consider basic leading principles of research designs that forms the basis upon which methodologies are implemented (Burch and Robinson, 2007). In this study, the framework aims to demonstrate how vulnerable critical systems are evaluated through scoping, assessment and how the outcome is mainstreamed in the oil and gas industry. It demonstrates its hybridisation with a mix method approach of data collection and analysis in the Niger Delta context.

3.2 Literature Review for Framework Design

Four case studies implemented by practitioners and experts are reviewed to underpin the most favourable and academically acceptable framework that could be adopted for this research and investigation. These cases are reviewed carefully to deduce acceptable aspects that are inclusive and applicable in assessing both existing and developing infrastructures:

A. The Washington Department of Transport (WSDOT) conducted a vulnerability of critical infrastructures applying "owned infrastructures framework." Their approach allows selection of roads, railways, airports, and ferry terminals; as critical infrastructures for vulnerability assessment. This implies that other infrastructures at climate risk (example seaports, buildings, recreational and commercial areas) that do not fall within this frame were excluded. Therefore adopting "own infrastructure" vulnerability assessment suggests a high level of bias because there could be other more critical and vulnerable infrastructure out of the "own" systems. In addition to the argued bias, the approach could have addressed developing infrastructure which Fuchs, Heiss and Hübl (2007) argued that contemporary assessment must be inclusive and comprehensive so as to incorporate mitigating standards in the designing, planning, building and management of assets. On the contrary, however, in the context of climate change, industries are prompted with the need to protect their systems through collaboration, technology and information sharing. This study adopts specific infrastructures but incorporates interdisciplinary stakeholder and multi-stakeholder approach to reduce the bias arising from assessing own system.

B. The Federal Highway Administration (FHWA), US Department of Transport infrastructure assessment applied a framework for climate vulnerability assessment incorporating 150 infrastructures. This is contended to have exceeded their budget and time frame (FHA, 2012). They resolved to downscale the list by rigorous "combination and elimination method". Assets not likely to be affected by certain risks under preview were eliminated and vice versa. The method is criticised for lack of theoretical merit and discriminate interdependent vulnerable critical systems (Agrawala et al., 2012). Exclusion of assets of high intrinsic value such as recreational centres, residential buildings, and hospitality centres could rather increase the vulnerability of included infrastructure in the context of extreme climate change impacts. (Moteff and Parfomak, 2004a) argued that the arbitrary elimination of several critical infrastructures framework due to resource constraints might miss the most vulnerable systems. Furthermore, this method could have captured developing assets as part of the "own infrastructure" to ensure that adaptive capacities are incorporated. Nonetheless, the generic inclusion of assets for assessment could compromise the quality of assessment and could be time-consuming and capital intensive. This study applies a systematic approach of selecting and eliminating systems through an objective stakeholder engagement and theoretical considerations.

C. In this case, the Australian Capital Territory (ACT) pilot study adopted a "stakeholder input" framework in the selection of new infrastructure for vulnerability assessment. The team argued that engaging stakeholders was strategic as it attracts funding and captured the attention of the government for knowledge sharing and technology transfer. Kloprogge and Van Der Sluijs, Jeroen (2006) contended that a complete stakeholder-based framework in vulnerability assessment of infrastructures could be affected by stakeholder bias, which could compromise the expected rigour of selection and eventually affect the validity of the outcome. However, unlike other frameworks, the ACT approach is inclusive of developing infrastructure, inclusive of stakeholders and could incorporate adaptations against environmental burdens. The methodology for stakeholder engagement was dialogue and generic decision making. This study adopts AHP to implement decision-making and to eliminate bias from framework design.

D. The fourth framework was constructed by the Science Application International Corporation (SAIC) in the vulnerability assessment of highways as escape routes in case of a terror attack. SAIC provides a comprehensive guide (including stochastic models) from a security vulnerability assessment perspective with a focus on critical infrastructures such as bridges, roads, tunnels, gas pipelines etc. Systems incorporated are claimed to have equal exposure and could be equally impacted by climate risks. But their framework lack stakeholder engagement and choice formation and failed to indicate clear roadmap that captures developing infrastructures as part of climate impact assessment. In this study, the framework provides an integrated pathway that captures and include developing infrastructures in assessment process where the central compressing plant/central processing facility (CCP/CPF) emerges in the study. The overarching aim is to ensure that vulnerability assessment is encompassing and holistic.

From the reviews above, a framework for vulnerability assessment of critical oil and gas infrastructure in the Niger Delta context is constructed. Some of the weaknesses highlighted are considered to ensure that most critical vulnerable systems are selected for assessment within time and available resources.

3.4. Constructed Framework for this study

Technically, the framework is constructed for both single and multiple researcher-based approaches, unlike expert based mechanisms, which are ambiguous and complicated for academic operations. In academic research, time and resources are often limited but the framework is designed to capture salient dimensions:

i. General Scoping
ii. Developing infrastructure scoping
iii. Vulnerability assessment
iv. Mainstreaming

The framework argues that in scoping infrastructures for analysis, developing infrastructures are included in vulnerability analysis. The aim is also to recommend imbedding climate adaptive capacities in the design, building and installation of critical infrastructure in the Niger Delta case.

3.4.1 Scoping

This dimension sets the purpose of the research background by determining the major aims, objectives, main questions, and knowledge gap as may be applicable in the industry. It creates an opportunity for review of the extensive literature to understand research background and documentation of infrastructures of interest as well as inherent climate burdens in the study area (Kalaugher et al., 2013). It also involves a critique of the historical perspectives of climate impact on infrastructures in the study area to ensure that appropriate research frames and pathways are identified. These pathways include processes of data collection and analytical tools, focused objectives, timing, planning and other resources to be involved (Yuen, Jovicich and Preston, 2013; Frischknecht et al., 2007). The pathway is illustrated in *Figure 16*.

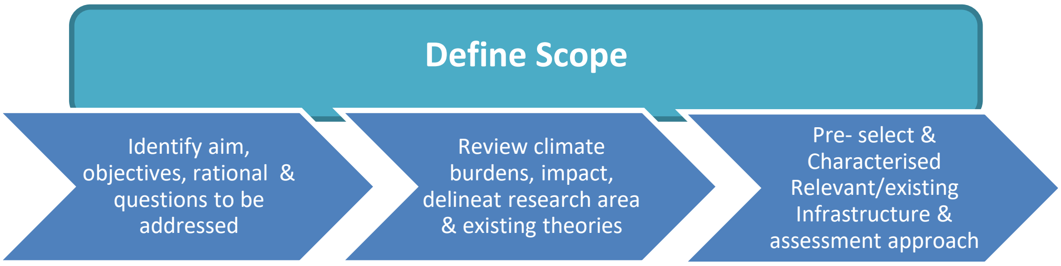

Figure 16; components for Defining the scope in the framework

3.4.2 Developing Infrastructure Scoping

This dimension suggests that developing infrastructures are captured into the assessment process depending on vulnerability indicators around the infrastructure and its sensitivity. Arising from this dimension, a separate research design may focus on assessment of developing infrastructures vulnerability to climate change impacts, considering presence of climate burdens, vulnerability indicators such as proximity, exposure, criticality etc. (Maleki et al., 2018). In this study, developing infrastructure in the research area are investigated and incorporated for assessment. Practitioners could adopt this model to aid their resistance building process for critical infrastructures. This is to avoid regrets associated with climate impacts in the in the oil and gas industry and to ensure that sustainable adaptation strategies are maintained. Timely decision-making is crucial in the management of critical infrastructure vulnerability to climate change because of systems' economic importance and the overbearing cost of losing them to climate-related disasters (Hinkel et al., 2014).

Nonetheless, Agrawala et al (2012) and ACT Government (2012) argued that for studies involving developing projects, a component of climate impact assessment should be included in the Environmental Impact Statement (EIS) to ensure that adaptation options are incorporated into the system design from the developmental state. This suggestion is acknowledgeable in the industry as it creates opportunities for climate impact assessors to participate in EIAs scoping, reporting and prediction. Climate impact assessment could be emerging systems of assessment and infrastructure value proposition in the oil and gas industry under the climate change phenomenon. *Figure 17* shows the processes involved in developing infrastructure assessment either for a single researcher approach of an integrated aspect of conventional studies.

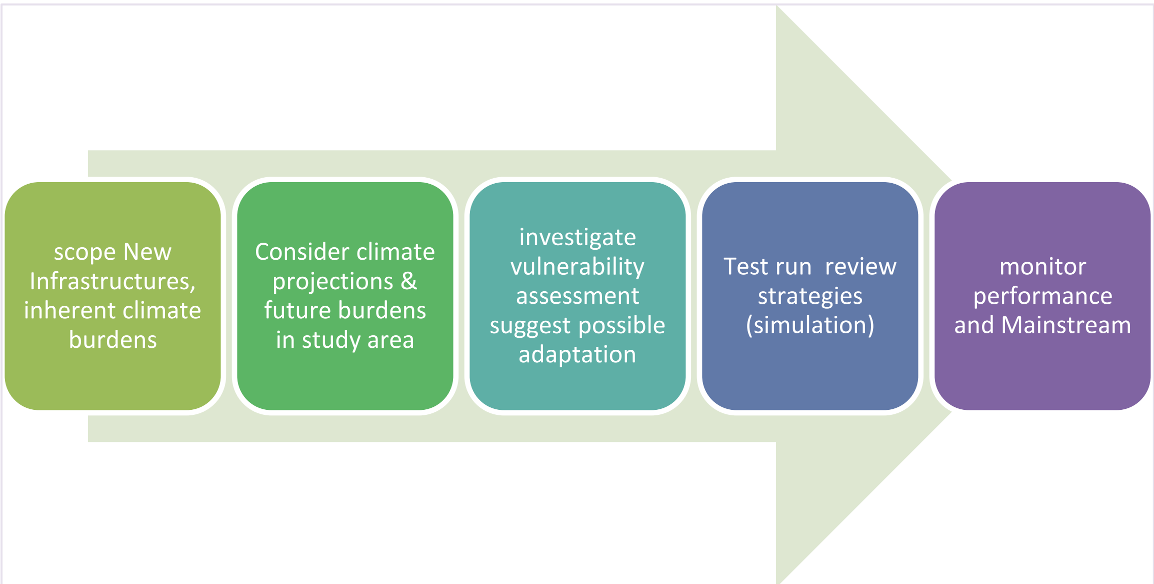

Figure 17; components for assessing Developing Infrastructures

3.4.3 Vulnerability assessment

This section demonstrates how the major assessment pathway involving selected methodologies is applied. It incorporates a systematic data collection and analyses using appropriate approaches such as stratified focus groups, face-to-face interviews, etc. It demands that a clear understanding of the dynamics of infrastructures and climate burdens are clearly earmarked and tools for data collection are assembled. In this study, AHP is applied in the assessment to ensure that most vulnerable and critical systems are considered due to resources and time. AHP shapes the research validity and presents a clear approach for selecting the most critical infrastructure for vulnerability evaluation involving multiple systems in different locations (e Costa, Carlos and Vansnick, 2008).

Vulnerability assessment in this study encompasses stakeholder engagement, criticality evaluation, vulnerability assessment, analysis of critical systems, recommendation of adaptation alternatives, operationalising (mainstreaming) outcome and review of performance (*Figure 18*). In addition to the application of AHP, this study aims to triangulate the design by collecting documentary evidence from infrastructures assessment logbooks, policy frameworks and embark on observational investigation. Triangulation involving qualitative data from literature, structured focus groups, and observational data is suitable for the implementation of AHP in vulnerability assessment (Bayazit, 2005). The outcomes of the overall assessment including adaptation measures could be reviewed due to uncertainties in climate change systems in research area as well as proposed for mainstreaming.

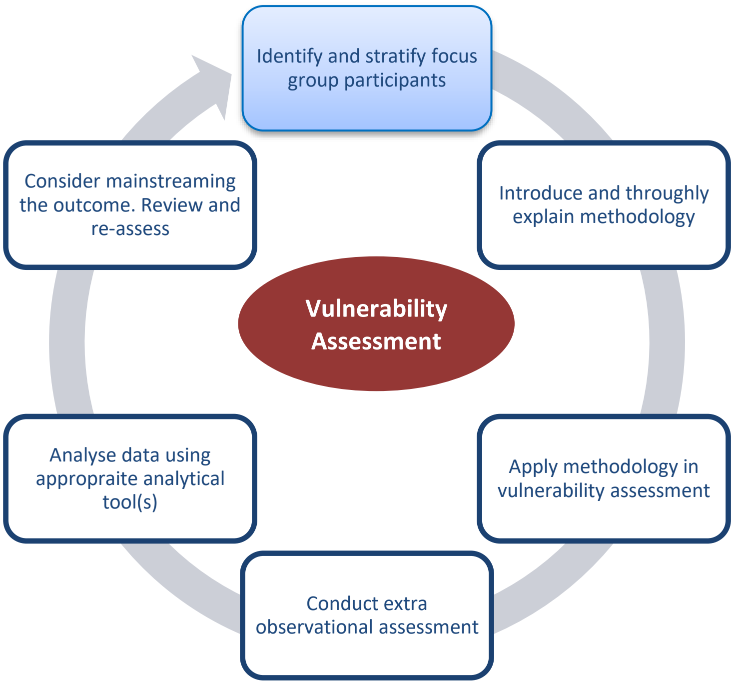

Figure 18; components for the Vulnerability assessment

3.4.4 Mainstreaming

Expectedly, findings are mainstreamed in; 1) industry and practice, 2) government policy-making and 3) further research and training purposes. Mainstreamed outcomes are subject to monitoring, evaluation and reviews to ensure that there is an updated practice resulting in an iterative assessment process (see *Figure 18*). Mainstreaming is one of the ways of commercialising research findings by implementing the suggested outcome in the field (Rauken, Mydske and Winsvold, 2015). Mainstreaming climate adaptation, impact and vulnerability assessment framework into institutional assets management plan with a focus on addressing assets resilience and resistance would be critical in the oil and gas industry. It is the best practice that could provide the required protection of the industry from severe impacts of climate change such as flood, extreme flood events, heavy rainfall and rising temperature. This is because unlike mitigation, adaptation addresses immediate issues and curtail impacts of socioeconomic dimensions of the economy. Mainstreaming further allows for long-term decisions to incorporate emergency and risks management, project prioritisation, adaptation planning and investment education and engaging stakeholders and decision-makers (See *Figure 19*). The overall design for assessing the vulnerability of critical oil and gas infrastructure is constructed as shown in *Figure 20*.

3. <u>Framework mainstreaming</u>

- Incorporate into infrastructure management policy (for emergency planning and disaster risk management, contribute to long-term adaptation planning and project prioritisation).
- Awareness creation (bridging the knowledge gap, building public confidence and create investment opportunities)

Figure 19; the components of integrating results into decision-making framework by Government of concern agencies

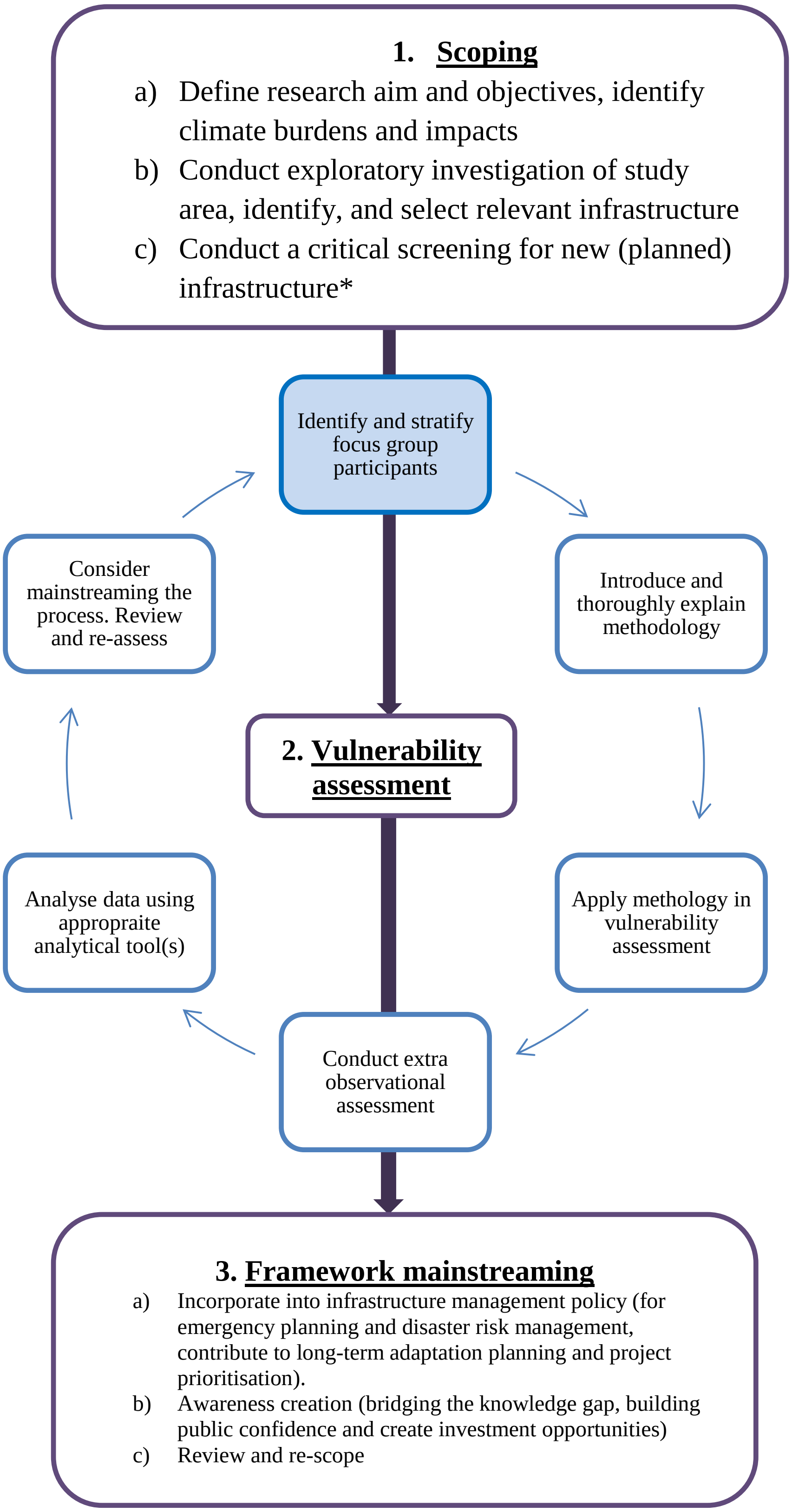

Figure 20; Framework for the vulnerability assessment of oil/gas infrastructure

3.5 Framework principles

The idea of climate change vulnerability assessment using a conceptual framework in this study is derived from models applied by experts in organisations involved in vulnerability assessment, backed by academic theories. This framework is a critical aspect of this study as it aimed to establish a new impact assessment model that supplements the conventional Environmental Impact Assessment. The framework principle captures four crucial niches that allow its fit for climate vulnerability assessment:

3.5.1 Integrated and Flexible Approach: - The framework is designed to ensure that financial, economic, environmental, social and cultural factors are considered in climate vulnerability assessment. It also shows a level of flexibility in information searching while the outcomes are mainstreamed in decision making and policy making, training and assessment.

3.5.2 Risk Assessment and Management Approach: - The framework sets a path for accurate climate change burdened determination and provides an opportunity for the evaluation of uncertainties associated with climate change. It ensures that critical infrastructure assessment outcomes are accompanied with optimum adaptation. Summarily, the framework aims to identify climate burdens, their impacts and provides adaptation strategies for mostly the oil/gas industry.

3.5.3 Shared Responsibility Approach: - the framework adopts a multidisciplinary approach drawing responsibilities from experts within Managerial and field agents; to collectively underpin vulnerability of delineated infrastructures. Sharing responsibility is critical in the Niger Delta assets management where oil/gas systems are operated on joint ventures with community involvements through corporate social responsibility (Idemudia, 2014).

3.5.4 Iterative Assessment Approach: - the vulnerability assessment section of the framework sets an iterative process that defines a procedural arrangement involved in the assessment of critical infrastructures. Review and continual assessment in a cyclical order ensures that infrastructure life-cycle and obsolescence, climate projections and uncertainties are adequately considered. Adequate consideration of these indices ensures that the adaptive capacities of systems are constantly upgraded in line with the changing climate. The iterative content of the framework simplifies the process of decision making in terms of planning, investments and prioritising infrastructure upgrade.

3.6 Chapter Summary

This chapter presents a review of experts and theoretical viewpoints in frameworks and underpins interplaying elements that allow the combination of industry and academic approaches of vulnerability assessment. The design is suitable for a multidisciplinary assessment approach for both existing and developing oil and gas infrastructures. It emphasises scoping for climate risks, setting the aims, objectives, rational and illumination of study relevance in the context of this study. Importantly, the framework acknowledges that developing systems could be vulnerable from design and installation stages and created a section that incorporates developing infrastructure in the assessment. The central part of the design focuses on an iterative vulnerability assessment component; taking into consideration field approaches such as introduction and application of methodology in data collection, observational assessment and data collection and data analysis. The last segment, mainstreaming, of the framework, aims to integrate the outcome of analysis and possible recommendations into industrial asset management code and possible vulnerability assessment process. It is expected that the outcome could influence decision-making and policy development as well provide the bases for training and awareness creation in the industry.

This framework is applicable to other non-oil and gas sectors and can be adapted according to the aims and objective of assessment. It further provides an opportunity for application of multidisciplinary multi-stakeholder research and analysis from a generic perspective as inadequate in other framework designs. The next chapter demonstrates a methodological pathway that operationalises this framework for data collection in a multi-stakeholder process and application of the analytic hierarchy process (AHP) as the quantitative method of data analysis in this study.

CHAPTER FOUR
RESEARCH METHODOLOGY

4.1 Introduction

This chapter presents the methodological pathway of the study and explains how data was collected, analysed and interpreted. It further illustrates the implementation of two paths of the study framework with focus on re-scoping the climate burdens and oil and gas infrastructure to corroborate findings and arguments arising from the literature. It describes elite, semi-structured, and focuses group interview processes in two sections drawn from the study framework for the research area. In addition to the interview data, observational and documentary data on flood risks models and location of critical infrastructure were obtained to illuminate the theory of vulnerability of the Niger Delta.

4.2 Research Philosophy

Social science investigations generally focus on explaining various phenomena encompassed within available evidence, though constructing what constitutes evidence is controversial especially how evidence (data) is collected and analysed (Goodson and Phillimore, 2004). Exploring research philosophy forms the underpinning knowledge from nature and theoretical assumptions based on global research perspectives that could direct how evidence is collected. However, research philosophy attempts to craft a link between theory and research which is contended as never straightforward due to; theoretical content and data collection could build or test existing theories (Bryman, 2016). Based on this, research philosophies are either epistemological, ontological or methodological paradigms (Scotland, 2012; Goodson and Phillimore, 2004). Ontological paradigms focus on realities and nature of social systems that compels researchers to identify the real existence of issues and how they function. Epistemology, on the other hand, is concerned with the formation of knowledge. It is rather concerned about how knowledge is created, learnt and transmitted.

Each paradigm has its individualistic limitations and assumptions which underpinnings could lack strong empirical evidence. Different paradigms inherently contain views which differ depending on ontological or epistemological perspectives, hence the difference in the "assumptions of reality and knowledge which underpins their particular research approach" (Scotland, 2012).

The methodology component of research paradigm is concerned with a set of the strategic plan of actions driven by choice of approaches that address how, why, what, and when data is collected and efficiently analysed (Harvey, 2010; Gomm, 2008). It emphasises on how a researcher plan to go about the investigation of emerging issues from literature. Generally, methods are specific strategies applied in collecting and analysing data (qualitative or quantitative) using ontological or epistemological paradigms. Qualitative methods present interpretive statements of others with the aim of exploring knowledge. This could be obtained from documentary evidence, interviews, opinion pool, and observational investigations that collectively constitute data sets. Qualitative research is inductive and extends its synthesis to the detailed behaviour of a given sample stratified for data collection. The exploration of this paradigm is to enable the most suitable research methods that satisfy both ontological and episcopal lenses of this study.

The quantitative approach, on the other hand, is argued to be a deductive empirical strategy that deals mostly with statistical outcomes, which are often collected through administration of questionnaires. The quantitative approach could also scope data from surveys, laboratory experiments, and randomised block designs and analysis (Amaratunga et al., 2002). It measures the trends of samples development, compares events from the numerical representation of total samples. With this background, some elements of quantitative research approach were adopted to collect and analyse data in this study.

A third research approach combines quantitative and qualitative methods and has been widely applied in contemporary science and social investigations (Johnson and Onwuegbuzie, 2004; Creswell et al., 2003; Amaratunga et al., 2002). The aim of combining these approaches is to optimise the validity and accuracy of result leading to triangulation. Mixed method research provides detailed information and captures both tangible and intangible arguments that could arise from a study. The joint analysis using appropriate techniques produces reliable outputs that justify outcomes (Bryman, 2012) and have been extensively implemented in this study.

Ontological and methodological paradigms were adopted for this study because of its focus on the realities of social and critical systems (oil and gas infrastructure) that were identified and evaluated from empirical existence. The study was conducted through a methodological framework that collects qualitative and quantitative data that underpins their functionalities.

4.3 Research Strategy

In this section, the mixed method research strategy and concepts adopted for this study are discussed. Justification and how the study fits into a mix method strategy and implemented to elicit data from stratified participants is described.

4.3.1 Justification of Mixed Method Strategy

Mixed methods research arises because of the weaknesses associated with individual qualitative and quantitative research methods. Hence the proposition of mixed method social research strategy is to combine various strengths of the individual approach while offsetting their combined weaknesses in data collection and analysis. Though this strategy is opposed by some researchers, it has continued to occupy both social and science investigations since 1980 (Bryman, 2016). Therefore, the mixed method strategy is a study that hybridised both qualitative and quantitative approaches in a single investigation. Example of mix method research is the combination of a semi-structured interview with focus groups or structured interviews with observations in collating both quantitative and qualitative data. In addition, a mixed method strategy has become a widely used approach in the industries for social science research, including vulnerability assessments (Bryman, 2016; Gomm, 2008; Sandelowski, 2000). This study, therefore, adopts a mixed triangulated strategy for the assessment of vulnerable critical oil and gas infrastructure to climate change impact in the Niger Delta.

4.3.2 Justification of Triangulation Strategy

Combining qualitative and quantitative research (mixed methods) involves some empirical approaches that primarily bridge the nuances between both strategies. These approaches include triangulation, completeness and offsets. Triangulation of mixed method strategy implies that the outcome of research involving a given approach is compared with the findings of some research involving another approach (Bryman, 2016). He argues in the light because there is confidence in the validity of the research outcomes involving qualitative method if it could be verified by applying alternative concepts or strategies of evaluation. Other researchers have triangulated qualitative interviews to check the validity of quantitative data and argued that it makes the overall result robust and acceptable (Silva and Wright, 2008). It has been further contended that triangulation bridges the gaps in the weaknesses and strengths associated with each research method. Bryman (2016) concluded that the limitations associated with either qualitative or quantitative approach can undergo completeness by combining a mix method strategy. It implies that gaps in qualitative studies could be 'completed' (closed) by combining quantitative approaches to produce a robust and valid result. For research validity, data were obtained from interviews, observations and documentary evidence (triangulation). Sandelowski (2000:251) illuminated the argument by claiming that *"…whenever there is a discrepancy between what participants do and say they do [reality], what observers see participants doing is generally considered a more accurate reflection of reality than self-report"*.

This study, therefore, adopts a triangulated mixed method strategy to ensure that qualitative, quantitative and documentary data was obtained through interviews and observations in examining critical infrastructure in the Niger Delta. The weaknesses of qualitative or quantitative data are compensated for or offset by each of the methods and complemented by field observation.

4.4 Review of Research Methods

This section presents a review of methodologies applied in this study, and exploratory investigation to determine the fieldwork process. It describes how data was collected from desk literature review, interviews, documentary evidence and application of multi-criteria decision-making tool (AHP) in quantitative analysis. Other interview approaches adopted for this study (focus groups and face-to-face semi-structured elite interviews) are reviewed in this section to demonstrate the study pathway.

4.4.1 Desk scoping for Infrastructures and Climate Risks

Desk review provides background opportunity for investigating relevant climate risks and infrastructure in the study area. Scoping for infrastructures at risk or inherent climate burdens is a crucial aspect of the study (Garnaut, 2008; Salathe, Mote and Wiley, 2007). Infrastructure arising from the literature are contained in

Table ***1*** and *Figure 9*.

Though literature scoping revealed several infrastructures that could be vulnerable to climate change, it was challenging to include all in this study due to available time, resources, scope and complexities associated obtaining data in the Niger Delta. However, it is argued that a combination of literature and data obtained through the preliminary investigation could further delineate scoped infrastructure to most relevant systems for focused analysis (Correa and Yusta, 2014). Relevant systems could have been missed if the focus is given more to the desk review approach (Bryman, 2012). This limitation necessitates an exploratory investigation involving stakeholders in the study area to ensure that infrastructures from the literature are relevant to the study of climate change impacts.

4.4.2 Exploratory investigation

Researching in Nigeria is very challenging. There are no existing databanks for ease of the challenges associated with collecting primary data, hence sampling organisations and participants for this study was tedious. Moreover, collecting data from the oil and gas industry in the Niger Delta is even more challenging, time-consuming and highly bureaucratic especially during the period of crisis. A three (3) months exploratory (preliminary) investigation was conducted in the Niger Delta to sample oil and gas companies and their specific requirements for external research visitors. The aim was to further investigate the procedures for conducting an observational field investigation and limit scoped oil/gas assets from literature to the most valuable. The exploratory investigation provides the opportunity to obtain the requirements for interviewing Management (elites) staff and Assets management crew in the sampled companies. The exploratory survey and preliminary interactions allow the selection of seven (7) valuable systems for criticality analysis and include:

i. Terminals
ii. Wellheads
iii. Pipelines
iv. Flow stations
v. Roads and bridges
vi. Loading Bays
vii. Transformers and High voltage cable

However, the exploratory investigation also revealed a list of paperwork and proofs of confidentiality from the research sponsor and the institution upon which the study is based. Marshal and Gretchman (1995:83) argued that "interviewer may have to rely on sponsorship, recommendations, and introductions for assistance in making appointments with elites for interviews." To address this challenge, the following letters were obtained:

- ✓ letter of introduction from the Thesis Supervisor
- ✓ Proof of sponsorship from research sponsoring Agency – Petroleum Technology Development Fund (PTDF)
- ✓ Proof of recognition of research obtained from Petroleum Regulatory Agency in Nigeria – Department of Petroleum Resources (DPR)
- ✓ Short research proposal
- ✓ Application letter from researcher requesting for the opportunity to conduct this study stating details of staff category to be interviewed and extent (duration) of the study

To obtain the approval from DPR, a separate letter of introduction was obtained from PTDF to ease accessibility of the Port-Harcourt Office in the Niger Delta.

4.4.3 Interview Approach

Interviews are verbal conversations between two or more people, or one person (the interviewer) and the other (participant(s)) to elicit thoughts, information, understanding, opinions and experiences by the use of questions (Anyan, 2013; Barton, 2012). Interviews have become a popular approach for interdisciplinary researches where the interviewer controls and drives a discussion. It is an acceptable method of data collection that investigates deeply about perceptions and views in direct participation with properly stratified participants (Oliver, Serovich and Mason, 2005). Interviews can either be structured, semi-structured and unstructured; forming a continuum shown in *Figure 21*.

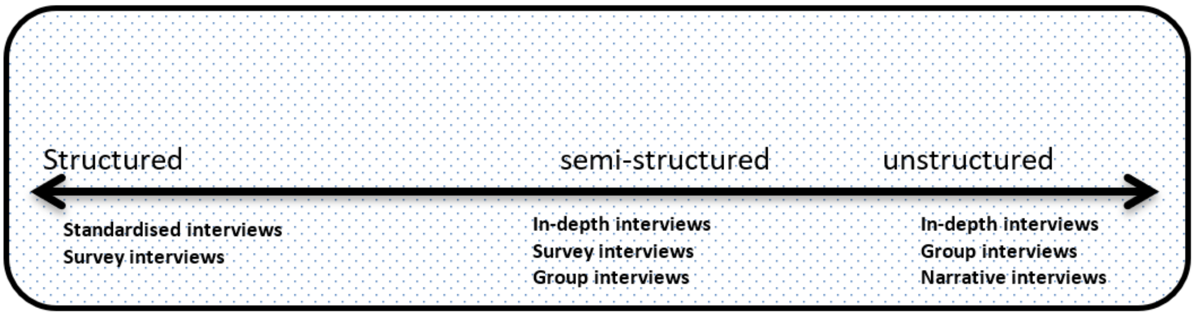

Figure 21; showing the interview structure in research. Source: (Bob and Ross, 2010)

A structured or standardised interview takes a predetermined set of questions asked exactly in the same order and manner even when repeated with a different participant. It requires that the interviewer ask questions using the same words for each interview that provide information from a set of options provided by the researcher. This implies that if the options are not properly constructed, the participants are compelled by the approach to complying without adjustment, which may question the validity of the research outcome (Bryman, 2016). Secondly, the application of a structured approach in multi-criteria decision-making is not required because AHP is already structured for criteria-based assessment adopted for this study. It is also inefficient in this study because it is restricted to a face-to-face meeting between the participants and researcher without opportunity for eliciting data from questions not initially captured in the questionnaire (Oliver, Serovich and Mason, 2005; Bob and Ross, 2010). However, it is strictly for collecting exact data for an approach but might suffer if an unexpected issue evolves during fieldwork. Hence, this study adopts an alternative semi-structured approach to guide against the disadvantages associated with structured interviews.

The semi-structured interview approach mediates between the structured and unstructured interviews (see *Figure 21* above). It contains an element of predetermination of common questions for each process but allows reasonable flexibility on the part of the participating informant thereby providing an opportunity for the introduction of new, evolving and follow-up questions (Wiesner and Cronshaw, 1988; Barton, 2012). Data from semi-structured approach are analysed with data obtained through other sources or interviews adopted for this study. It gives the interviewer the liberty to introduce a context as deemed appropriate for each interview session while the participants address the questions using their own words, unlike the structured interview where a set of alternatives are provided. It is argued that "No interview can truly be considered unstructured" but it can be relatively unstructured equivalent to guiding a research conversation (DiCicco-Bloom and Crabtree, 2006).

Unstructured interviews, on the other hand, focus on broad oral narratives. It gives the informant(s) more opportunity to drive the interview process than the researcher (Gomm, 2008). This is seemingly risky because the informant may usurp the process with easy and provide irrelevant information that may ruin the integrity of the findings. Interviews can, therefore, be granted by any stratified group of people such as elites and uneducated depending on objectives. In this study, the semi-structured elite interview was adopted for face-to-face data collections to ensure that participants discuss extensively and present relevant data with an opportunity for asking follow-up questions.

4.4.4 Elite interview

Elite Interviews are specialised cases designed with a focus on special research participants (Marshall and Rossman, 1995). Elites in this study context are influential, knowledgeable, and prominent informants stratified for interview in Nigeria oil/gas companies. According to Carol—where (1995) and Harvey (2010), they are stratified for special interviews due to their wealth of experience, expertise and relevance in a given study area. The aim of focusing on semi-structured elite interviews was based on the argument that elites offer valuable and more authoritative data that suffices the study (Harvey, 2010). The significance of the elite's inclusion in this study is to scope their wealth of experience on historical antecedents on environmental issues in the region. Their role also includes providing strategic decision framework available from the industry on the future of critical oil/gas infrastructure with attention on climate change impacts. Furthermore, elites are planners and fundamentally influence budget and adaptation accounting, making them suitable respondents in this study. Due to their position, they are more likely to provide documentary data needed in this study.

However, elite interviews are associated with some demerits. Elites are usually operating on tight schedules making their accessibility challenging. They are difficult to reach as most corporate executives ring fence themselves from the public domain in the Niger Delta (Idemudia, 2012). Another challenge is that elites enjoy the predilection of their experience and may mesmerise the interviewer, thereby taking over the interview process. To contend with this, interview appointments were pre-booked within a tolerable period and ensured that schedules were kept. The semi-structured interview gives the researcher the opportunity to control the session thereby minimising the risk of take-over by the elite participant(s). In this study, two separate forms of the interview were applied for effective data collection;

a. Semi-structured elite interview and
b. Focus groups

4.4.4.1 Semi-structured Elite interview approach

Semi-structured elites interview approach was adopted for this study because of the research aimed at exploring deep information from highly knowledgeable participants with the view of asking follow-up questions. It offered a complete opportunity to elicit opinions, views and understanding that contributed to the validity of the study outcome. It is argued that the validity factor is required for a reliable conversational investigation (Wiesner and Cronshaw, 1988). Nineteen (19) elites were stratified and interviewed in Shell Petroleum Development Company (SPDC), AGIP, Total Exploration and Production and Alcon Oil and Gas Services.

4.4.4.2 Focus group approach

In social research, focus group surveys (made up of 7 – 12 participants in each group) have become popular in social science research (Gomm, 2008). It involves the organisation of participants with relevant experience and expertise in administration, engineering, finance, and policy; for data collection using interviews (FHA, 2012; Barbour, 2008). Though it is argued that the result from stakeholder's input might be subjective due to personal experience (Kloprogge and Van Der Sluijs, Jeroen P, 2006), implementation of triangulation in mixed methods for this study reduced the element of bias as argued. It further reduced subjectivity and established an opportunity for averaging inputs and explored complementary sources of primary data collection (Al Khalil, 2002). In this study, elite participants were selected through random sampling framed by their position, duration of employment and only those in active service in the Niger Delta oil and gas industry. Accordingly, Managers and Asset Managers of Assets and Physical Infrastructure, Environment, Health and Hygiene, Engineering and Maintenance were selected and participated in the face-to-face interview.

4.5 Multi-criteria Decision Analysis (MCDA)

Multi-criteria decision-making analysis is a complex multi-level process with several analytical tools such as analytic network process (ANP), multi attributes decision making (MADM), multiple objective decision making (MODM), and analytic hierarchy process (AHP). These sections provide insight into why AHP was adopted as an analytical tool for this study.

4.5.1 Analytic Hierarchy Process (AHP)

AHP has increasingly gained relevance in both industrial and academic types of research involving critical decision-making using specific criteria or indicators for prioritisation of alternative elements (Yu, 2002). Criteria for assessment are indicating standards upon which decisions are made. AHP provides a technical approach to managing multiple choice alternatives and solving complex problems through justifiable decisions (Yousefpour et al., 2012). It creates an opportunity for researchers to focus on most crucial systems through a consistent and logical mechanism by decomposing the decision-making process into parts (sub-elements). Analysing each part independently and combining the parts to produce meaningful results (Al Khalil, 2002; Tzeng, Lin and Opricovic, 2005). When applied in multi-stakeholder studies, it harmonises and aggregates each stakeholder's views from group brainstorming, and trade-offs of some factors or options (NRLI, 2011). AHP has been applied in analysing economic, social, industrial, environmental, agricultural, and industrial energy-related studies similar to this research and its data (Al Khalil, 2002), hence its consideration for this study.

It was adopted for this study with the view that it will pave the way for a strategic decision on issues with a high degree of uncertainty, high stakes, major implications and long-term consequences in the context of climate change (Montibeller and Franco, 2010). It eliminates the researcher's bias and other difficulties associated with subjective decision making and allows for multiple evaluations through focus groups data collection (Al Khalil, 2002). AHP generates ratios that illuminate how much an item is more important than others, hence its wide acceptance implementation in industrial studies (Montibeller and Franco, 2010; Fowler et al., 2014).

4.5.2 AHP framework

AHP framework is designed in three (3) basic hierarchical levels; decomposition of the decision problem and setting the goal, synthesis and decomposition of criteria into sub-criteria (where applicable) and identification of 'alternatives' to be prioritised (see *Figure 22*).

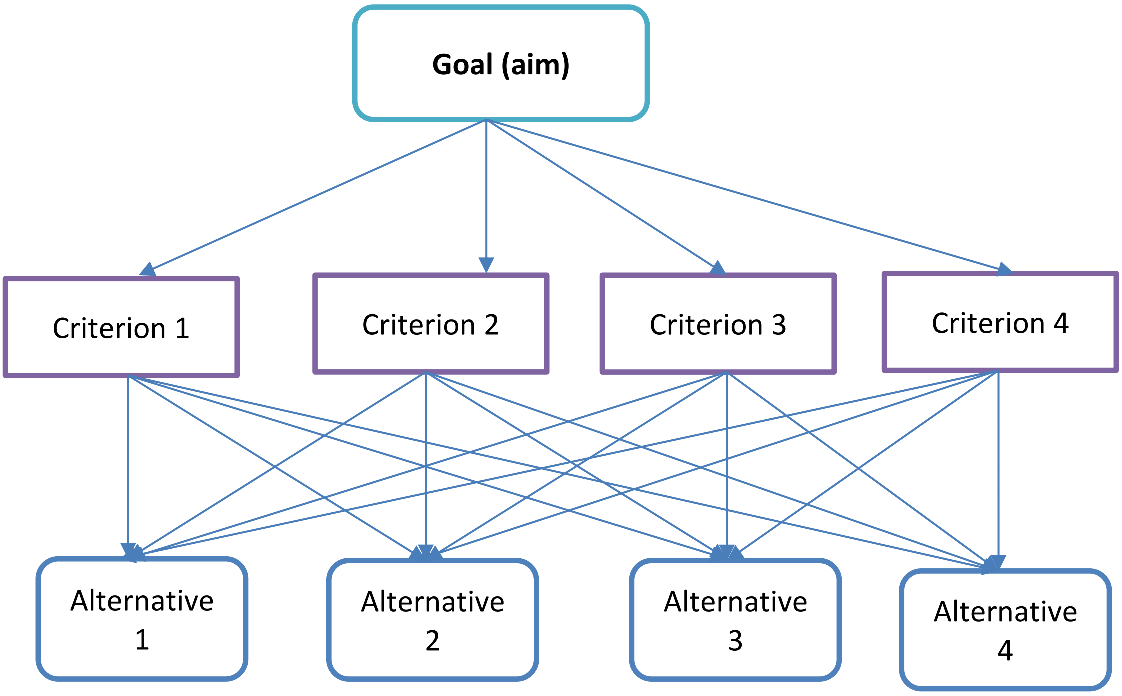

Figure 22; AHP framework for prioritising alternatives

The goal is the aim of the study, which is pre-determined from literature or stakeholder interaction in a focus group (Bayazit, 2005; Gühnemann, Laird and Pearman, 2012; e Costa, Carlos A Bana and Vansnick, 2008). Criteria and sub-criteria were the parents and child nodes that guided the participant's decision-making process in this study. The sub-criteria further illuminates' importance of a parent criterion on alternatives (Tzeng, Lin and Opricovic, 2005). Selected infrastructure for this study were the alternatives prioritised for both criticality and vulnerability. The next section highlights the limitations associated with applying AHP from previous studies.

4.5.3 Limitations of AHP

AHP is limited by the challenge of capturing convincing criteria for assessment and understanding of uncertainties associated with interfacing input parameters that could yield a valid result (Al Khalil, 2002). This is though opposed by Gühnemann, Laird and Pearman (2012) who argued that AHP is open to the integration of external analysis such as cost-benefit because it facilitates alignment with infrastructures and can account for economic impacts not easily captured with other tools such as the ANP. AHP is restricted by the number of alternatives and criteria that could be simultaneously analysed at a time per given study. (Goepel, 2013b) argued that a maximum of seven (7) indicators or alternatives is suitable for any given assessment to reduce complexities and increase the validity of output. This creates a choice for the researcher to construct and indicators and alternatives to ensure conciseness and reduced complexity, stress arising from data collection analysis which could become uneasy to understand.

In this study, these challenges were considered at the early stage of research and minimised. A systematic literature review (page 28) was applied to decompose relevant criteria and sub-criteria for criticality and vulnerability assessment. To ease determination of how many possible comparison outcomes could arise from 'n' number of criteria and alternatives, a simple mathematical model; $\boldsymbol{n(n-1)/2}$ is applied. This justifies the scepticism of some authors who contended that pairwise comparison in AHP may be difficult to calculate possible comparison pathways with multiple alternatives (Yousefpour et al., 2012; Dong et al., 2010; Yu, 2002).

4.5.4 Application of AHP in this study

Managers and Assets Management crew (Engineers, Environment and Safety Officers) with at least ten (10) years' experience in the Niger Delta oil and gas industry were selected and engaged in focus groups and one-to-one interviews. The focus group was conducted in three segments:

i. Brief re-scoping exercise to ensure that selected infrastructures are appropriate for the study and to ensure that developing systems were captured in the data collection phase. This was also an opportunity to introduce the process of completing the AHP questionnaire.
ii. The focus group completed the questionnaire for a criticality assessment. Participants could dialogue shed light on emerging issues. The discussion was recorded as part of the qualitative data.
iii. In the third segment, participants completed the criticality and vulnerability assessment questionnaire for further analysis of critical infrastructure.

4.6 Prioritising Critical Infrastructures

AHP was applied to prioritise selected infrastructure based on criticality. The purpose of prioritising the infrastructures into critical and less critical systems was to determine which assets are more sensitive for vulnerability assessment. Generally, AHP is applied to reduce the number of systems and alternatives for assessment by selecting the most critical in order of priority outcome, for further analysis. In this study, the pre-selection was carried out by engaging with stakeholders at the exploratory (preliminary) investigation stage. Prioritisation technic is suitable for a single researcher with limited time and resources; as contained in the study framework. The generic framework is shown in *Figure 22*.

4.6.1 Deciding the criteria through Pairwise Comparison:

The criteria for prioritising critical infrastructure (section 2.5) were ranked and rated based on participants' perception of how important each applied to climate impact assessment in the Niger Delta. The ranking was conducted through pairwise comparison applying Satays' fundamental ordinal scale (1 – 9) shown in *Table 5*; for any two alternatives (*i and j*)) (Passos and Souza, 2013; Saaty, 2003). Pairwise comparison is a fair process for prioritising multiple systems and help the researcher to understand the weight of each criterion and how the vulnerability of infrastructures could be influenced. The outcome of such studies informed judgements and critical decision on assets management in the oil and gas industry.

Table 5; Saaty's Fundamental scale (Passos and Souza, 2013)

Numerical scale	Verbal scale (interpretation)
1	Equal importance (*i* = *j*)
3	Moderate importance (*i* is lightly important than *j*)
5	Strong importance (*i* is strongly important than *j*)
7	Very strong importance (*i* is very strongly important than *j*)
9	Extreme importance (*i* is extremely important than *j*)
2, 4, 6, 8	Intermediate values

4.7 Assessing vulnerable Infrastructures

Criticality assessment presents a list of infrastructures generated in their order of criticality. In this section, the study is focused on vulnerability assessment of 'critical' oil and gas infrastructures, unlike the first case, which focuses on how the criticality assessment of the infrastructures was conducted. Since infrastructures were pre-selected and refined through AHP, all seven (7) are considered critical for vulnerability assessment; located within the vulnerable coast of the climate impacted Niger Delta. The aim of vulnerability assessment is to achieve the major research objective; *"To assess the vulnerability of oil and gas critical infrastructures to climate change impact in the Niger Delta."*

4.8 Research Analysis Approach

Different data sets were proposed and collected for this study. Each was tied to a unique analytical approach that addresses research aim, objective and questions. Goepel (2015) multiple AHP input spreadsheet was used in analysing criticality and vulnerability data obtained from focus groups involving multi-stakeholders' inputs. The consistency of stakeholder's participation and overall principal eigenvalues for ranking infrastructures was determined by a consistency ratio (expected at about 15%) and priority vector using Mi-AHP.

4.9 Chapter Summary

The chapter describes the strategy and methodology that was applied for data collection and analysis for this study. It adopts a mix method strategy with the aim of eliciting both qualitative and quantitative data for analysis in combination with the literature review to effectively triangulate the strategy. Accordingly, the strategy involves scoping data from secondary sources, exploratory survey, and face-to-face semi-structured and focus group interviews. The face-to-face interview is structured to elicit data from elites while the focus group aimed to apply analytic hierarchy process (AHP) in scoping quantitative data from groups of engineers, environmental officers and maintenance engineers in the oil and gas industry. It further presents details of multi-criteria decision-making analysis (MCDA) including its tool such as the analytic network process (ANP), analytic hierarchy process (AHP), etc. AHP is carefully reviewed – stating the limitations and merits for its implementation in prioritising and selecting from multiple choices. The chapter described how the analytic process for criticality and vulnerability of infrastructures was conducted in line with the research framework; implementing the Mi-Spreadsheet.

CHAPTER FIVE
REFLECTION ON FIELDWORK STRATEGY

5.1 Introduction

Strategies for empirical social research in the Global South can differ significantly from conceptual understanding and existing theories applied in the Western world (Cohen and Arieli, 2011; Bulmer and Warwick, 1993). Though existing theories and methods could potentially signpost a researcher, they are often challenged by environmental factors prevailing in different study areas and empirical strategies. Other issues include time allocated for the study and unstable political environment which could lead to failure and destabilisation of the entire research structure. Academics have argued that the conditions and approaches guiding social research in developing countries seem to differ significantly from those in the developed world, hence suitable approaches could be designed to suit a given environment (Bulmer and Warwick, 1993). In recent years, these differences have been aggravated by political crises in the Niger Delta, for instance, making empirical studies cumbersome, time-consuming and almost impossible in some industries such as the oil and gas. It is being contended that the research area or industry could influence the research strategy and theoretical applications, which differ between regions. These differences cannot be ignored else the fundamental principles that border on the realities of any social research could be missed (Hoskisson et al., 2000; Parker and Kirkpatrick, 2002; Wright, 2015). In this chapter, an in-depth reflection on the outcome of fieldwork strategies, the failure and adjustments are presented in the Niger Delta perspective.

5.1.1 Researching the Niger Delta

Crude oil exploration, transport and pollution have continued to trigger a perennial crisis in the Niger Delta for over two decades (Anifowose et al., 2012). Major debates on the Niger Delta are centred on the phenomenon of “resource curse” which characterise the poverty of the people arising from low economic growth, environmental pollution from the oil spill and poor health condition of the people. This is notwithstanding the highest mineral wealth of the region as an energy hub of Sub-Saharan in Africa. The multifaceted issues have continually excited youths in the region into an unending crisis that over time has led to kidnapping activities and blowing off critical infrastructures such as pipelines, manifolds, flow stations, wellheads etc. These actions have severely impacted the smooth operations of multinational oil companies leading to high-security alert systems, frequent declaration of force majeure and shutdown of activities across the industry value chain. These industrial responses not only pose challenges for the industry but significantly obstruct external activities such as research involving interviews, physical examination of assets and training in the Niger Delta.

The responses mentioned above potentially hinder the smooth application of existing theoretical social research strategies. Though focus groups, face-to-face interviews, field observations, and collection of documentary evidence could be justifiable methodologies that have received a scholarly commendation in eliciting data in social research, political crises such as the case of the Niger Delta could frustrate the conventional approaches (Ungar, 2008; Harkness, Super and Rubin, 2006). While these strategies could work in western cultures due to political stability and a general awareness of the importance of research; it was very challenging applying these theories in researching the Niger Delta as it may be the case in other developing climes (Parker and Kirkpatrick, 2002).

5.2 The need for multiple strategies

A multiple or dual research approach in this context of the Niger Delta involves two or more strategies for data collection from the field. It involves effective planning for unforeseen circumstances that may emerge in the process of conducting fieldwork in an unfamiliar environment. Given these challenges in the Niger Delta, research sceptics and proactive planners are expected to engage in dual or multiple strategies especially for studies involving stakeholder participation, direct observation and other approaches of data acquisition. To incorporate dual strategy, a careful examination of the research area is crucial as it enables the exploration of other effective research practices and their success levels in the practical environment (Edejer, 1999; Emanuel et al., 2004; Lavery, 2004). In this study, a pragmatic dual strategy that underpins the environmental and social principles of the study area was applied to nuance the possible impacts of failure arising from existing theories. Understanding the working principles of the Niger Delta has informed how data was successfully collected for this study and is presented to educate both foreign and local future researchers on the challenges of social research in the region and how to mitigate them for successful fieldwork.

The reflection attempts to discuss in details how formal and conventional theories were applied and challenges encountered in the fieldwork in relation to the oil and gas industry. The section presents the cause of existing strategy failure and adoption of informal strategies as an alternative to elicit data within the appropriate time and available resources.

5.3 Implementation of Formal Strategies

A formal research strategy (page 60 to 70) was designed from literature to elicit data for this study. All the requirements and prerequisites gathered from 4.4.2 Exploratory investigation were timely obtained and submitted appropriately. Hard copies of essential requirements were manually delivered at the customer service receptions of five (5) companies identified for this study and allowed for internal processing and response. Three (3) weeks after submission, one of the companies responded via email stating that:

"We received your letter on the above-titled request and wish to thank you for your interest in Nigeria LNG Limited. We regret to inform you that we will not be able to accommodate this request at this time. Kindly accept our best wishes for success in all your endeavours and assurances of our highest regards"

A further attempt was made to request for explanation through phone calls and it was gathered that the research is not of interest to NLNG because climate change is not a challenge for their infrastructure. This response and the complete dormancy of other organisations caused a complete collapse of the formal research strategy which could have altered the entire fieldwork. However, while the strategy for data collection was inventively managed, entering the stratified companies for data collection was elusive. This necessitated a pragmatic decision and a careful study the reasons for disruption, reviewed the processes and proceeded the fieldwork.

5.4 Reasons for Entry Disruption (failure)

A reflection on the causes of entry strategy disruption is documented to show how alternative approaches were employed to achieve the aim of the study and to bring to reality the challenges of researching crisis-prone regions. The reason for this chapter is to buttress awareness of the risks associated with fieldwork in organisations operating in volatile regions. This is for future researchers who might be interested in the Niger Delta.

5.3.1 Bureaucracy

Generally, bureaucracy is a system of leadership that is applied in controlling and managing many employees in an organisation according to laid down rules, regulations and control of activities (Picur and Riahi-Belkaoui, 2006). It is contended that oil companies, government agencies, educational institutions and the private sector depends on the mechanism of bureaucracy to function effectively (Meyer, 2015). How bureaucracy in the context of this study has become a disenabling mechanism for researching successfully in the Niger Delta is central to this sub-section. As argued, bureaucracy is enshrined in the oil and gas industry and the Nigerian public service for quality control and allowance for a wider opinion before decisions are finally made (Rasul and Rogger, 2018). *Figure 23* shows a typical brief bureaucratic schematic in an oil company in the Niger Delta. In this study, a request to conduct brief research was addressed to the General Manager who could decide to reject or accept the request or call for advice from subordinating Managers – say R&D. The Manager (R&D) could further request the inputs of Assets and Environmental Manager because the research sits within their departments and they played a significant role in the interview process.

The Managers for Assets and Environment scheduled a meeting to appraise the request and ensure that all required supporting documents are obtained from relevant authorities such as the Department of Petroleum Resources. Once a decision is made, it is feedback through the communication channel as bureaucracy requires back to the General Manager who could request that the researcher is communicated on approval or disapproval. Approval presents the second tier of bureaucracy through the Human Resources and Legal Departments. In this study, this bureaucratic chain was indefinite and resulted in the failure to gain formal entrance. It is argued that bureaucracy breeds corruption and create an opportunity for unjust opinions that constrain creativity and expression of research opinions (Hirst et al., 2011). This theory could have caused the initial neglect of research request by oil and gas companies in the Niger Delta. It was gathered that some staff in the bureaucratic chain were on field inspection, annual leave and highly engaged, hence, the delay in response. It is assumed that external research appeals are less important to oil companies, which could have contributed to the bureaucratic bottlenecks that frustrated the conventional research plans.

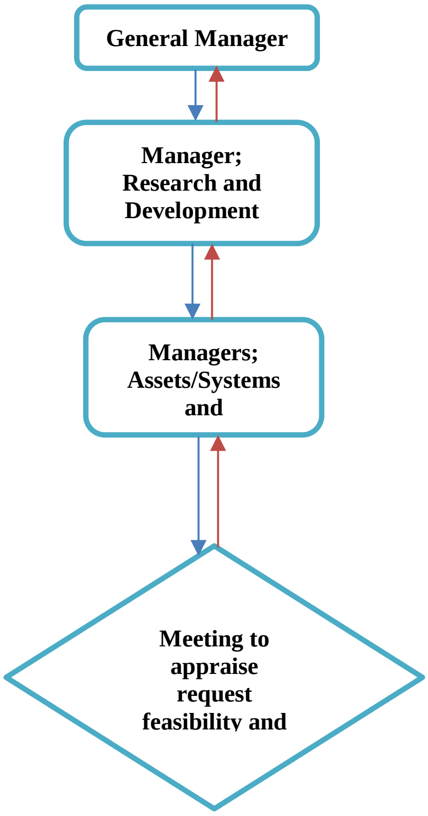

Figure 23; A brief bureaucratic system in a typical oil company

5.3.2 The phenomenon 'No Response'

Every piece of research activity is time bound for effective resource utilisation and delivery, hence, the pro-activeness and effort of the researcher is paramount to getting responses from the proposed participants. Unfortunately, a *'no response'* culture of the oil companies to external issues in the context of the Niger Delta appears to have stalled the conventional data collection process. Oil companies in the region tend to give more attention to host communities due to fragility and pending crisis and respond to the regulatory agency than external research requests. This phenomenon and busy schedule of organisational elites are suspected to have contributed to the complete neglect of research appeal for this study, hence the disruption of formal research entry strategy. This confirms the opinion of Carol—where (1995) and Harvey (2010) who argued that elites are always on a tight schedule and working with them could be frustrating and time-consuming.

5.3.3 Limited Data

The inability of Oil Companies in the Niger Delta to provide climate impact data and the global blame on the industry for being responsible for anthropogenic emission could have deterred companies from responding to a request that focuses on climate change (Fischer and Knutti, 2015). More so, companies with insignificant inputs on climate change phenomenon could demonstrate reluctance in accepting researchers whose aim could potentially trigger a new narrative compelling company to action climate adaptation plans. Nonetheless, 3 weeks of concerted effort to get a response, some companies advised resubmission claiming that initial submission was not documented. In addition to lack of climate data, requesting for a resubmission indicates that some multinational oil companies apparently have poor information management system which requires significant improvement in inter-organisational climate adaptation planning.

5.3.4 Cultural Attitudes

Attitudes of respondents and ethical issues of proposed research organisations significantly affect data collection and could be considered in preparing for fieldwork (Bulmer and Warwick, 1993). Freedom of information legislation mandates organisations and individuals to grant responsible access to credible information but due to attitudes and experience, it does not guarantee access to data in the Niger Delta oil and gas companies. In this study, cultural attitudes were found to hinder response to the research. Attitudes are one important factor to consider in researching the Niger Delta. According to Bulmer and Warwick (1993), the "…often uncompromisingly hostile attitude of the [people] towards…" research and visitors may daunt enthusiastic investigators. This factor played a significant role in causing the failure of formal entry research strategy during the fieldwork for this study.

It was also found that failure could have arisen from personal neglect by prospective individual participants that were not obligated to grant interviews despite approval. Some expert demonstrated a bias for the study of climate change as it threatened crude oil sustainability in the global market systems.

5.3.5 Security Risk and Ethical concerns

Over the past two decades, the Niger Delta crisis due to the activities of militants and kidnappers has heightened security concerns in the oil/gas rich region (C. Obi, 2014; Agbiboa, 2013; Okoli and Nachanaa, 2016). At the wake of 2016, a new group of militant – Niger Delta Avengers (NDA), emerged and declared war against critical oil/gas infrastructures compelling the federal government to address critical issues in the region. The gravity of militancy and insurgency caused a declaration of a force majeure and activation of 'red security alert' across production platforms and all industrial areas. This situation which coincided with the fieldwork schedule of this study made it impossible to access administrative offices as well as field operators. Significant screening of visitors delayed the process at the detriment and frustration of this study. A complete deviation from initial plans.

Aside from the security concern, companies expressed high ethical concern on confidentiality and data protection systems in place to ensure that data released will be used for only research and academic purposes. Intensive screening of consent and supporting documents from relevant authorities (e.g DPR) was conducted to ensure that all ethical procedures were followed. Unfortunately, initial endorsement by relevant institutions failed as companies failed to grant acceptance and access for data collection.

However, a strategic adjustment of the strategy was made to widen the chances of accessing companies and obtaining valid data from original participants. The approaches are reflected in 5.5 below as possible strategies for researching successfully during a crisis in the Niger Delta as may be applicable in other regions in the Global South.

5.5 Implementation of Informal Strategies

These are informal adjustments deployed when conventional formal social research approaches failed (Joshi and Sthapit, 1990). They include all adjustments of activities that could result in loosening existing protocols as much as reasonable to allow formal activities to take place without altering the quality, relevance, and validity of datasets (Martin, 2004). The success factor of informal approach, in addition to loosening access control, is its ability to reach original participants, by-passing and curtailing delays resulting from the dormant response, human attitudes, cultural issues, bureaucracy, less ethical and security checks. It minimises expenses and maximised time allocated for fieldwork. These include *informal contacts, follow-up and snow-balling.* These approaches have been applied in social research to elicit valid data when it is obvious that formal strategies and theories could become cumbersome and time-consuming (Browne, 2005a; Bulmer and Warwick, 1993; Cohen and Arieli, 2011; Loury, 2006; Ponomariov and Boardman, 2008; Teng and Faff, 2017).

5.5.1 Implementation of Informal Contacts

Genuine refusal of access to the intended research area can be frustrating and discouraging but understanding what to do next is fundamental. The utilisation of ‘Informal contacts’ and the role of gatekeepers could substantially improve situations (Crowhurst and Kennedy-macfoy, 2013). It involves engagement of gatekeepers and contacts (external and internal) who are acquainted with the industry and are willing to release data or create linkages with relevant participants who may be willing to release desired data *based on trust* (Loury, 2006; Minkler, 2005; Ponomariov and Boardman, 2008). In this context, 'influential personalities were employed to negotiate opportunities for data collection and further paved the way for the smooth signing of confidentiality agreements. Influential contacts also vary depending on the status of the researcher(s), research relevance and the complexities arising from the social environment (Dahl and Pedersen, 2004).

Researching in the conflict-prone region such as the Niger Delta by the foreign or local individual researcher was very challenging, hence the setbacks. Therefore, influential contacts such as politicians, directors of supervisory agencies such as DPR, security personnel and relevant staff of the oil and gas company played a significant role towards data collection for this study in the Niger Delta. Though not explored in this study, community liaison officers are also crucial gatekeepers that could potentially penetrate companies and facilitate informal meetings. In the Niger Delta, the powers of the community can never be underestimated as DPR, National and International Oil Companies (IOCs) hold them to high esteem as part of corporate social responsibility (Ijaiya, 2014). Community Leaders know and understand the regional mechanisms coupled with the CSR obligation of IOCs makes them very relevant stakeholders whose endorsement and intercessions are often trusted (Minkler, 2005).

However, implementation of formal contacts did not negate the conventional procedures involving supporting documents and endorsement from the relevant agencies as stated on page 72. All documentary evidence including confidentiality agreement and ethical issues were carefully scrutinised and supervised by the legal department of respective companies. In some companies, applications were resubmitted through an informal bottom-up approach of processing to curtail the bureaucracies involved in the flow of information.

5.5.2 Follow – up Strategy

'Follow-up' is a fundamental phenomenon for monitoring the movement of applications and request made to both public and government institutions in Nigeria. Approaching institutions without adequate preparation for follow-up could be time-consuming, discouraging and an attempt to undermine the purpose of business in Nigeria (Sofola, 2014). To manage this study's fieldwork successfully, 'follow-up' approach was implemented to monitor the movement of mails, the influence of gatekeepers and other informal contacts to ensure a faster response. It involves strategic meetings, visits, telephoning, emailing, and continual lobbying with the aim of achieving entry approval across government and oil companies. Meetings away from the official environment where opportunities for an extra explanation of the research rationale, objectives, and how data would be used. Follow-up ensures that satisfactory and timely attention was given to requests after informal meetings. This concept further ignites a bond of friendship and increases rapport that reassures managers and other participants of the safety and confidentiality of data that was released. It serves as an enabler for knowledge sharing on background issues on climate change and industrial adaptation attempts. Follow-up strategy eliminated initial protocols/bureaucracies and prompted further linkages and snowballing with relevant individuals, departments and organisations for more data collection.

5.5.3 Snowballing

Snowball sampling in field research is implemented when the population of participants in a sample frame is either low or the topic under research appears sensitive to be considered for open discussion (Browne, 2005b; Teng and Faff, 2017; Sadler et al., 2010). In this study, the stratified sample size for the face-to-face interview was as small as the population of Manager Elites and expert technicians in the oil/gas companies are also few. This makes the implementation of snowballing strategy effective and suitable for this study. First, participants in the interviews identified created and facilitated the snowballing of the researcher to other relevant stakeholders or colleagues found credible for interviews. This agrees with the records of Sadler et al (2010) who claimed that during the conflict, snowballing can facilitate access to and improve co-operation from sampled participants. This strategy was replicated in all the companies and proved very effective, reliable and efficient for social research data collection (Cohen and Arieli, 2011).

However, it was found that the success level of Snowballing may depend on how effective the researcher is able to convince each participant at each stage of the interview chain. Secondly, the success of snowballing depends on the influence of the initial contact person; the higher the cadre, the more likely is it to be accepted by the next interviewee and vice versa. In this research, an effort was intensified in creating informal relationships with influential contacts and gatekeepers who continued to create internal links with relevant managers that were interviewed. General Managers and Managers of relevant departments such as Assets

Management, Environment and Safety, Research and Development and contracting Engineers contributed data that was analysed in this study to achieve its objectives.

5.6 Fieldwork outcome

Notwithstanding the initial setbacks caused by bureaucratic bottlenecks, poor response, limitedness of data, attitudes, security risks and tight access control systems, the strategic adjustments (informal contacts, follow-up, and snowballing) were efficiently and effectively used to obtain the desired data through face-to-face elite and focus group interviews. Nineteen (19) expert engineers participated in the focus group while fifteen (15) Managers participated in the face-to-face interview. Interviews were conducted in four (4) oil and gas companies (Mobile Producing in Qua Ibo terminal (QIT) Eket, Akwa-Ibom State, ALCON Nigeria Limited and Shell Petroleum Development Company (SPDC) in Yokiri Island, Delta state, and Total Exploration and Production Nigeria (TE & PN), in Port Harcourt, Rivers State. Audio records of interviews were made while graphics and documentary evidence of the historical 2012 flood disaster impacts were also obtained. Records of annual flood outlook 2015 and 2016 containing hydrological probable flood areas were obtained from Nigeria Hydrological Services Agency (NIHSA) while quarterly weather reviews for 2015 and 2016 were obtained from Nigeria Meteorological Agency (NiMET) to triangulate and substantiate analysis.

Furthermore, a direct observational investigation was conducted in relevant locations for the scoping of prevailing climate issues including the physical state of infrastructure, proximity to climate risks and adaptive compliance of developing systems. Historical data on flood, storms, and temperature change were obtained with an emphasis on the developing central compressing plant and central processing facility (CCP/CPF). The CCP/CPF is a critical infrastructure for gas monetisation which was observed as vulnerable due to a location in the low elevated area (4.5 metres above sea level). Based on the research framework, developing infrastructures are scoped during fieldwork and considered for vulnerability assessment. The inclusion of developing systems ensures that adaptation mechanisms are inbuilt from the design stage of infrastructure thereby making oil/gas assets resilient and resistant to climate change impacts (Phillips, 2015; Colenbrander et al., 2015).

5.7 Chapter Summary

This chapter presented a reflection on the failed application of conventional approaches in social research fieldwork, the crisis, causes and impacts and presents strategic adjustments that enabled the collection of primary data. It emphasises how crisis, ethical issues, attitudes and bureaucracy could delay the organisation's response and stall data collection in the Niger Delta context. Informal contacts, follow-up and snowballing are strategic approaches to researching successfully in Niger during the crisis. Table 6 summarises the datasets and the specific objectives fulfilled in tandem with research questions.

Table 6; Indication of acquired datasets and targeted objectives

S/N	DATASET	OBJECTIVES
1.	A critical review of published resources	(1) for the development of the conceptual framework and contributed to the achievement of other objectives
2.	Hydrological flood maps and annual flood outlook	(2) for vulnerability assessment of the Niger Delta to sea level rise and flood
3.	Focus groups interviews	(3) for criticality and vulnerable assessment
4.	Face-to-face elite's interviews	(4) To identify prevailing peculiar climate risks, evaluate and suggest sustainable adaptation alternative
5.	Observational graphical and documentary evidence	Provided primary bases for analysis that strengthened vulnerability and criticality assessment and justify the framework
6.	Documentary data on historical flood incidence	Was used to illuminate the criticality and vulnerability of infrastructure, justify the study framework, strengthened and form the basis for reviewing adaptation strategies

CHAPTER SIX
RESULT AND ANALYSIS

6.1 Introduction

This chapter focuses on the analysis of the result obtained from focus groups, face-to-face interviews, observational and documentary data. AHP questionnaire, sectionalised into two mutually exclusive parts, was used to collect data from focus groups for criticality (section one) and vulnerability (section two) assessment. The purpose of the criticality evaluation was to prioritise selected oil/gas infrastructure (*alternatives;* in AHP terms) in their order of criticality. Criticality investigation also strengthened and focused the study only on assets that require serious protection (adaptation plans etc.). It also avails the opportunity of streamlining analysis to highly prioritised assets for sustainable adaptation planning in the industry. Section two focuses on vulnerability analysis of 'critical' infrastructure and present criterion-by-criterion result and analysis. Section three evaluates the observational and documentary data to further illuminate and justify the vulnerability of infrastructure selected for this study. It argues that highly prioritised vulnerable critical assets are those that if impacted could have severe consequences on the economy, environment, and social construct of Nigeria and the oil/gas industry. See *Figure 24* for the framework of chapter analysis.

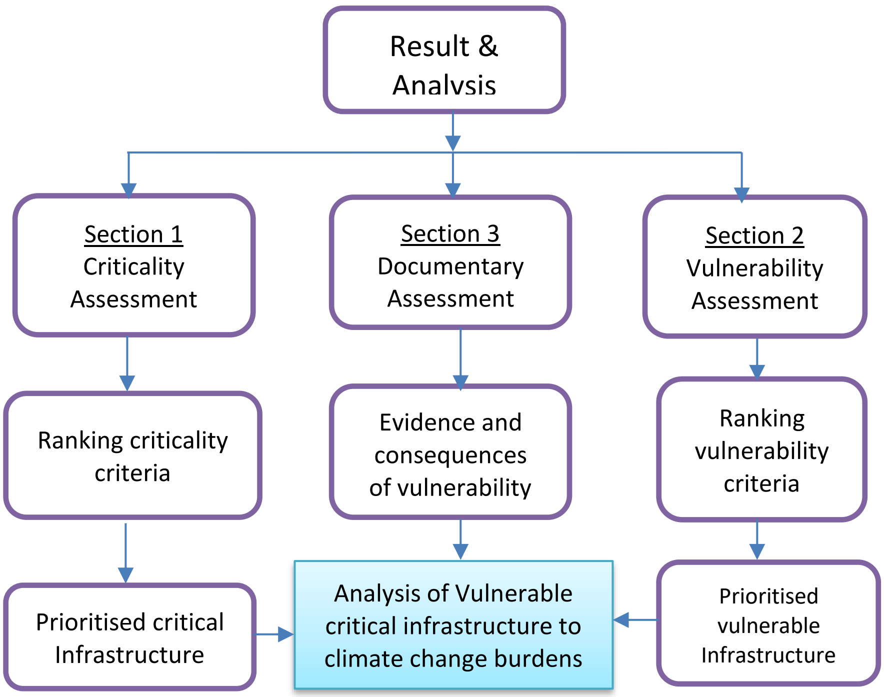

***Figure 24; showing framework for AHP analysis chapter* 6.2**

6.2 CRITICALITY ANALYSIS

The purpose of this section is to analyse and prioritise selected infrastructure in their order of criticality using analytic hierarchy process based on stakeholder perception. This analysis addresses the question of "what are critical infrastructures?" in this thesis and demonstrates the AHP methodological pathway upon which the critical infrastructures were ranked. The need for criticality evaluation evolved to systematically identify and justify named oil/gas assets as critical for adaptation planning focus. This is because there are numerous infrastructures in the oil/gas industry spread across the Niger Delta, too cumbersome for individual research consideration. Moreover, criticality assessment using AHP model requires that a limited number of alternatives (infrastructures) are considered for a purposeful in-depth/focus study. Using AHP in criticality investigation in this study eliminates experts' bias and partial judgement in selecting infrastructures for adaptation planning. It was found that criticality assessment signposts stakeholders in the industry to possible strategies for adaptation planning; with a clear indication on which infrastructures to prioritise and plan for in an event of climate change induced disaster. This is because participants in the study were to dialogue on possible strategies for mitigating rising Atlantic tides, sea level and temperature, flood risks and coastal storms.

The procedural pathway for criticality assessment beginning from deciding the goal of the investigation, determination of criteria and sub-criteria, to pairwise comparison is shown. Pairwise comparison is an AHP logic matrix approach of drawing conclusions by simultaneously ranking a set of two elements at a time to determine their importance or weight by assigning values (Koczkodaj, 1993).

6.2.1 Procedure for Criticality Analysis

AHP standards and sequential procedures were followed to analyse the criticality of selected infrastructure. See section 4.5 Multi-criteria Decision Analysis (MCDA). This section presents a step-by-step procedure on how selected infrastructures were analysed for criticality

6.2.2 Stratification of participants:

In this study, nineteen (19) participants consisting of field experts - engineers, environmentalists, health and safety professionals, assets maintenance and inspectors, participated in the focus group interview. Participants with a minimum of ten (10) years' experience in the environmental, assets management and operational activities, were systematically selected from four (4) major oil companies (represented by A, B, C, and D) within the Niger Delta. The study excluded students on industrial placement, community liaison officers and all other non-experts in infrastructure and environmental management. Four (4) independent focus groups of selected participants were formed in the four oil/gas companies in four locations within the study area. Constitution of each group was in the order; A = 4; B = 5; C = 5 and D = 5, (N = 19). Stratified participants have cross-border operational and consultancy experiences of two or more oil/gas companies in the region making their judgement rather universal and versatile in the study area. Gibson, Randel and Earley (2000) argued that grouping participants based on geographical experience for interview produces a better outcome than individual analysis provided that the study method is similar across groups within the same geographical features and among stratified participants with similar indicators. All participants were considered to have the same experience and robust knowledge of the Niger Delta oil/gas environment hence was given an equal weight of one (1). This implies that their judgement was considered as noticed in the arguments that evolved during the focus group.

6.2.3 Consistency Ratio (CR, α) setting

Consistency ratio is the measure of accuracy and persistence by participants in comparing the importance of any two alternative items. Conventionally used consistency ratio thresholds for AHP analysis is often 10% (Handfield et al., 2002; Sinuany-Stern, Mehrez and Hadad, 2000; Yu, 2002). In this study, the consistency ratio (α) in the multiple input spreadsheet was set at 15% (α = 0.15). The conventional threshold is effective where the researcher could revisit participants for repeat comparisons and adjustments of their judgements, which automatically improves the level of consistency. This approach compels decision-makers to alter initial judgements which may influence the result. Goepel (2013b) argued that a CR up to 15% is acceptable for a distant participation research strategy to accommodate differences that may arise. He, however, recommends the inconsistency ratio threshold of +0.1 to +0.5 as acceptable CR for all AHP evaluations. Furthermore, Saaty (2003) also argued that an extension (up to 15%) could improve consistency and the priority vector [and] allow decision makers original ideas to be judged. A consensus in AHP is the evaluation of agreement level from the random and independent pairwise comparison (usually by 100%)

6.2.4 Consensus level setting

In this study, consensus value was allowed at 100% to determine consensus ratio of participant's agreements in their decision-making. Consensus indicator ranges from zero (0) (where there is no consensus among participants) and 100% (for maximum consensus among participants). The consensus in AHP is used to determine the level of agreement where there is more than one participant in a rigorous decision-making process.

6.2.5 Participants Briefing and Criteria setting

Participants were guided through the information sheets and consent forms to ensure their willingness to participate in the study. A brief that defined each study term and criterion for assessment was explained through demonstrations with flip charts (see appendix I, II and III).

6.2.6 Numerical scale

The AHP questionnaire (see appendix V and VI) was completed based on the Saaty AHP standard linear scale (1, 3, 5, 7 and 9) for both criticality and vulnerability assessment.

6.2.7 Criticality Analysis (procedures)

This section presents a procedure for criticality analysis performed in AHP stages. First, the goal of assessment is set, and participants pairwise compared criteria to determine their specific weights.

Step 1. Goal Setting: the goal of this sectional analysis is to prioritise the selected infrastructures according to their "criticality"

Step 2. Comparison of the 4 major criteria (see appendix VII-XI): the four principal criticality criteria, were pairwise compared by participants in a pairwise matrix system. Their calculated weights are normalised to produce eigenvalues (EV) shown in a matrix *Table 7*.

i. The economic niche of infrastructure
ii. Environmental concerns
iii. Engineering capacity of assets
iv. Interdependency

The system of generating the pairwise comparisons using the usual mathematical approach can be cumbersome and complicated, but the AHP Mi-spreadsheet compressed the four criteria into a 4 by 4 reciprocated matrix by aggregating participant's inputs. In *Table 7*, the participant's input occupies the upper white view of the matrix while the lower grey section is automatically generated by reciprocating the upper values (1/n). Example, in one of the groups, participants felt that *Interdependence* (A) is more important than Economic Niche (B) by 6; 6 was entered the column for A x B and reciprocal automatically adjusted to 1/6. The aggregated result is shown in table 7:

Table 7; showing major four criteria weights and calculated ranks

MATRIX	Interdependence	Economic niche	Environmental Concern	Engineering capacity	Normalised principal Eigenvector
Interdependence	**1**	0.36	0.31	1.7	**13.80%**
Economic niche	2.81	**1**	1.28	3.51	**39.54%**
Environmental Concern	3.24	0.78	**1**	3.81	**37.06%**
Engineering capacity	0.59	0.28	0.26	**1**	**9.60%**

Each unit in the grey section is a cumulative matrix from 19 inputs and reciprocated by Mi - AHP contained in the blue section. The expression reflects the use of Saaty (2003) intermediary scale – 2, 4, 6 or 8; by some participants, which alter the fractional display.

Analysis: From the result, Economic niche was given the highest ranking followed closely by Environmental concern, implying that these are the most important indicators of concern in criticality assessment of infrastructures. Interdependence and Engineering capacity trailed with significance showing that it could be easier for the industry to repair mechanical systems than economic losses and environmental consequences. 74.1% consensus ratio was recorded and reflects the level of unconscious agreement that the economy and environmental concerns are important in the industry. A CR of 0.01 percent was also indicated. Consistency result in this section is significantly below the conventional threshold (10%) and indicates that participants were highly consistent with their pairwise comparison. This agrees with Yu (2002) who argued that the low consistency ratio indicates the accuracy of participants and their understanding of the pairwise comparison process. It further justifies the appropriateness of selected participants for the study.

Step 3; Comparison and Analysis of sub-criteria: In this step, three principal criteria were decomposed into two sub-criteria each and independently pairwise compared to obtain their eigenvalue (EV) weights in each case (*Table 8*). The aim of decomposing criteria was to synthesise and illuminate the intangible elements in any criterion and ensures that such associated elements are independently compared as criteria in the ranking. It also elucidates the weight of principal criteria when applied in analysing alternatives. It further justifies the thoroughness and meticulousness of AHP as a tool for the decision-making process in a multidisciplinary approach where the weighting system is used in ranking alternatives. The result of the sub-criteria comparison is shown in the table:

Table 8; the sub-criteria and individual ranks when compared under a principal criterion

Principal Criteria	**Decomposed sub-criteria**	**Scores (%)**	**Scale**
Economic Niche	Replacement cost	0.56	1
	Societal relevance	0.44	
Environmental Concern	Impact on ecosystem	0.59	1
	Impact on human health and safety	0.41	
Engineering Capacity	Availability of an alternative	0.47	1
	The effectiveness of the alternative	0.53	
Interdependence	Not decomposed		

Step 4; combined comparison and Analysis of criteria: In this step, decomposed sub-criteria are merged with the undecomposed '*interdependence'* criterion and jointly pairwise compared to obtain the overall weights for the seven criteria. Mi-AHP spreadsheet was used to evaluate the seven criteria weightings (adjusting the 'n' in Mi-spreadsheet to '7'). Participant's data was fed into the sheets and calculated accordingly. The resulting eigenvalues (in percentages) were re-normalised to '*1'* to obtain overall weights. Table 9 reflects participants' rating of the seven criteria as it can be applied in assessing the criticality of selected infrastructure in the study area. This result presents a set of synthesised indicators for practitioners and researchers involved in conventional environmental and climate impact assessment involving AHP for criticality assessment in other industries in the Niger Delta.

Table 9 Normalised weights of criteria

Interdependence	**0.07**
Replacement cost	0.07
Societal relevance	0.13
Impact on ecosystem	0.37
Impact on human health and safety	0.26
Availability of an alternative	0.05
Effectiveness of the alternative	0.05

Comparison matrix: ***Table 10*** below (also appendix XII) shows the comparison matrix summarised in

Table 9 above. It shows the aggregate result of each criterion from the participant's perspective and normalised principal eigenvalue column indicating the final weights of the criteria. These are applied in criticality assessment of alternatives with 85.3% consensus level.

Table 10; showing all seven criteria weights and calculated final ranks

Matrix	Interdependence	Replacement cost	Societal relevance	Impact on human	Impact on ecosystem	Availability of alternatives	Effectiveness of alternatives	**Normalised principal Eigenvector (%)**
Interdependence	**1**	1.29	0.46	0.2	0.17	2.48	1.39	**7.40**
Replacement cost	0.77	**1**	0.42	0.3	0.27	1.45	1.22	**6.84**
Societal relevance	2.18	2.36	**1**	0.33	0.22	3.07	2.69	**12.63**
Impact on human	4.93	3.3	3	**1**	0.52	4.33	4.91	**26.26**
Impact on ecosystem	5.86	3.71	4.57	1.91	**1**	5.06	4.91	**36.53**
Availability of alternatives	0.4	0.69	0.33	0.23	0.2	**1**	1.41	**5.19**
Effectiveness of alternatives	0.72	0.82	0.37	0.2	0.2	0.71	**1**	**5.14**

The consensus result indicates that among the 19 expert participants, there is about 85.3% agreement and acceptability which validate the result. The convergence to row EV in table 10 was obtained by dividing each normalised principal eigenvector in table 10 by 100. This produces the representative fractions entered in the decision-making hierarchical chart in figure 26. In the final comparison of seven criteria, the ranking result indicates that the impact on the ecosystem and human health and safety were ranked highest among others. As indicated in the previous ranking, threats to the environment and impact on human health are significant concerns in the oil and gas industry. More so, the supervisory agencies for oil/gas activities in Nigeria focus more on regulations to protect and reduce the impact of oil/gas exploration, production and transportation on the environment and human health

(Department of Petroleum Resources, 1991). Aside from the Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN), there are other regulations and guidelines closely monitored by the Department of Petroleum Resources (DPR) with strict actions on environmental violations in the industry. Some of these include Petroleum Regulation 1967, Oil Pipelines Ordinance (CAP 145 of 1956 and amended version in 1965) and Oil and Navigable Waters regulations 1968. Although it has been argued that these standards are outdated, the strict need for implementation by agencies of government always places environmental and human protection at the fore of the oil company's impact assessments. This might have informed the reason why participants in this study prioritise impacts on the environment and human health among other criteria for criticality assessment.

According to respondents, oil/gas company's operations are guided by ethics and values, which seek to protect people, environment, assets, and their reputation (PEAR). This could have inspired participants to give more attention to the environment and human-related criteria than others as indicated in the result.

The aggregate pairwise comparison process further shows that "*societal relevance*" - ranked 3rd, while *"interdependence"* and *"replacement cost"* - ranked 4th and 5th respectively. The relevance of the oil and gas industry to the Nigerian society is crucial as it forms the major source of national income and creates opportunities for small and medium enterprises to thrive around industrial areas. *Interdependence* and *replacement cost* of infrastructure appears to be the burden of management staff as they both were almost equally important. For *availability and effectiveness of alternatives,* which were both decomposed from engineering capacity, ranked 6th and 7th with about the same score. This is probably because participants consider the availability of effective systems to adapt to flood and other risks as the least mitigating options for criticality ranking. Furthermore, criteria such as *interdependence*, *availability* and *effectiveness of alternatives* found in the literature review and expert's reports justify the relevance of these indicators as could be impacted by climate change in the Niger Delta.

Step 5; Pairwise comparison pathway: This step shows the pairwise comparison pathway of the selected alternatives (infrastructures) using the criteria above. It presents the overall criticality evaluation pathway and procedure from step 1 (goal determination) to step 5 (pairwise comparisons of alternatives). Level 5 (figure 26) shows the outcome of criticality priorities obtained from Mi-AHP pairwise comparing spreadsheets.

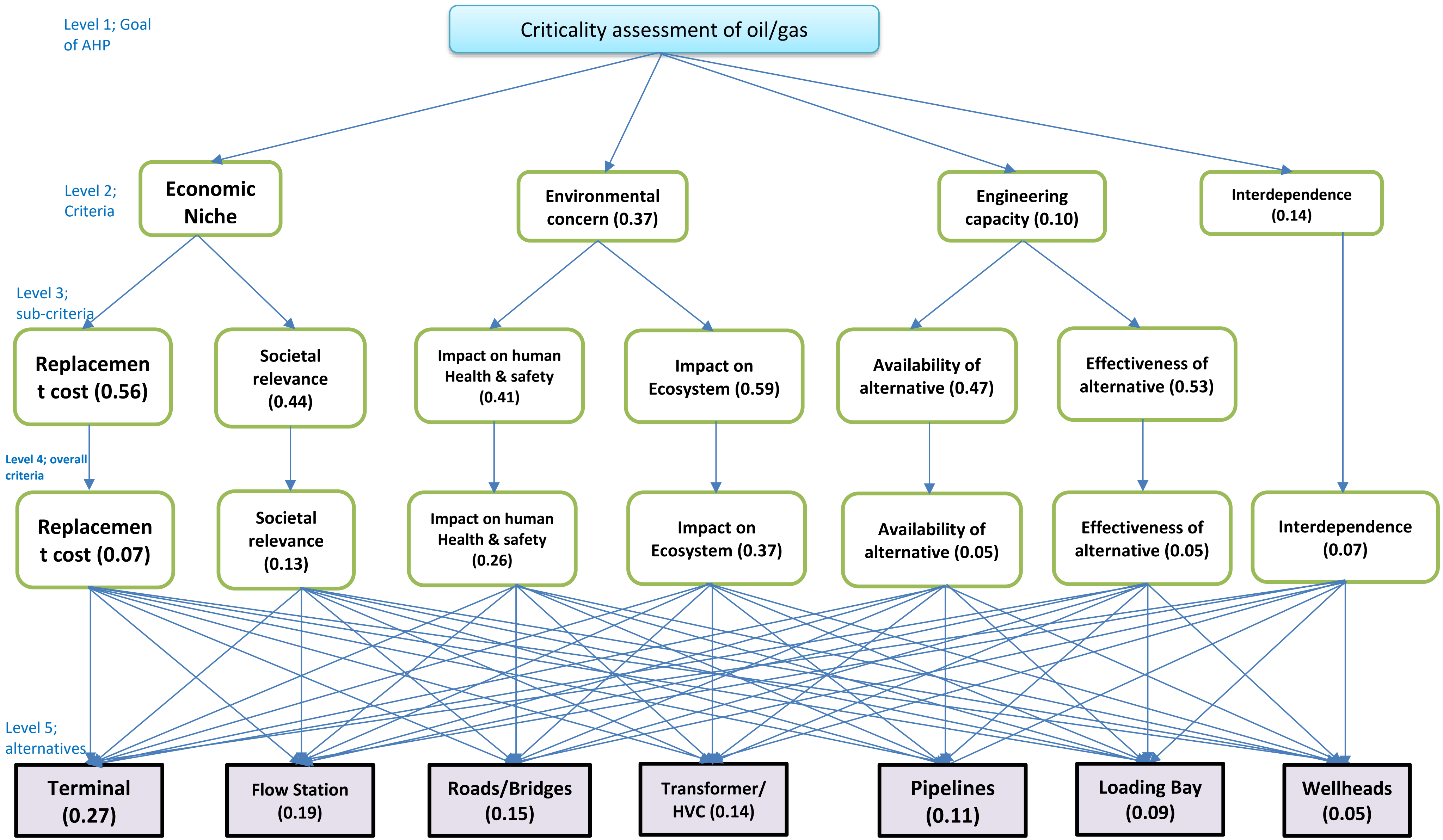

Figure 25; showing Criticality pairwise comparison pathway using Analytic Hierarchy process model

6.2.8 Prioritisation of Critical infrastructure

The comparison and ranking process of the alternatives (infrastructure) is demonstrated between level 4 and 5 of figure 26 above. Criteria outcome in level 4 was used to pairwise compare the seven alternatives in a matrix order shown with blue lines. An alternative approach to estimating possible number *'N'* of pairwise comparisons in a set *'n'* criterion is given by:

$$N = \frac{n(n-1)}{2}$$

Where n = number of items to be pairwise compared and 1 is a constant of equal importance excluded in the matrix. In this study; there were 7 alternatives or criteria; therefore,

$$N = \frac{7(7-1)}{2} = 21\ possible\ pairwise\ comparison$$

This indicates that there were 21 comparisons in the matrix of level 5 figure 26. Seven (7) separate Goepel (2015) Mi-AHP spreadsheets were created to systematically compute participant's decisions. In each Mi-AHP, 19 sheets were created to analyse each participants' pairwise inputs. An aggregated result is exported and presented; showing seven criteria by seven alternatives ranking in *Table 11*. Further analysis of each column of the table is presented in the next sections.

Table 11; showing overall result computed from Mi-AHP spreadsheet for criteria/alternatives

Criteria / Alternatives	Impact on Ecosystem	Interdependency	Societal Relevance	Impact on Human Health and Safety	Availability of Alternatives	Effectiveness of Alternative	Cost of Replacement	Total Score	Normalise Eigenvalues 1/7
Terminal	27.2	33.4	23.7	17.9	3.8	32	51.6	**189.6**	27.1
Pipeline	27.9	12.4	5.2	10.5	10.6	5.1	6	**77.7**	11.1
Flow Station	21.5	29.3	16.4	13.5	4	23.2	21.8	**129.7**	18.5
Oil well heads	11	4	4	4.7	3.8	4.6	3.3	**35.4**	5.1
Loading Bay	2.5	3.2	3.7	3.4	27.6	15.9	3.8	**60.1**	8.6
Transformer/HVC	5.7	10.1	21.1	22.2	23.7	10.3	6.3	**99.4**	14.2
Roads/bridges	4.2	7.6	25.9	27.8	26.5	8.9	7.2	**108.1**	15.4
TOTAL	**100**	**100**	**100**	**100**	**100**	**100**	**100**	700	100

Based on AHP principle of analysis, *Table 11* shows that each column has 100% scores distributed amongst seven infrastructures according to their criticality. This implies that for each criterion, participants ranked seven infrastructures by distributing 100 points according to their criticality. To indicate consistency and justify the ranking, each column is summed up to 100/100 = 1 to further indicate accuracy in the matrix process. This is repeated through the seven criteria as indicated in the columns and aggregated as shown in the orange column (total row score for each infrastructure) and normalised by dividing by 7 (shown in the purple column). The normalised eigenvalues = 1 shows the accuracy of the ranking process. The result, therefore, indicates that this study outcome is accurate and consistent with existing literature (e Costa, Carlos A Bana and Vansnick, 2008; Saaty, 2003; Bayazit, 2005; Jagtap and Bewoor, 2017).

6.2.9 Analysis of individual criteria outcome

This section presents a criterion-by-criterion analysis to show the ranking outcome of criticality and explains how each infrastructure could have been rated higher or lower than others (Appendix XIII-XIX). Face-to-face interviews were transcribed and extracted as quoted simultaneously in the analysis to further strengthen the analysis and present a deeper theoretical underpinning arising from the criticality of selected infrastructures.

i. **Impact on Ecosystem:** this criterion was designed to evaluate the criticality of infrastructure based on the impact it could pose on the ecosystems if being affected by climate change impacts. The higher the impacts, the more critical an infrastructure is perceived.

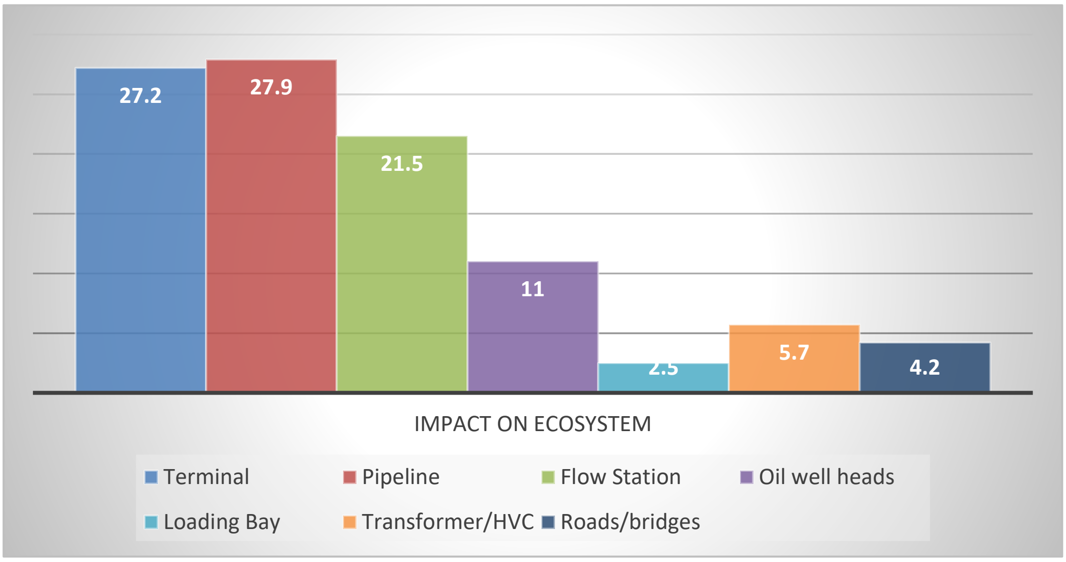

Figure 26 showing the criticality of infrastructure based on "Impact on Ecosystem"

From *Figure 26*, the criticality of infrastructure is presented as a measure of how the ecosystem could be impacted if the selected infrastructures are impacted by flood, storms, tides, corrosion, and rupture, etc. The level of impact generated from each infrastructure on the ecosystems determines its criticality (Theoharidou, Kotzanikolaou and Gritzalis, 2010b). The result shows that pipelines and terminals are the most critical followed closely by flow stations. This is because these systems occupy a very crucial niche in the separation, transportation, and storage in the value chain and always store crude oil in exorbitant quantities making them fragile, sensitive, and most critical. Pipelines appear most critical also because the impacts from usual interdictions and attacks had impacted the ecosystem severely (Anifowose et al., 2012). However, loading bays and Roads/bridges were ranked as the least critical infrastructure in terms of impact on the ecosystem, implying that when they are affected, there could transmit less significant impact on the ecosystem. This is though contrary to the position of (Suarez et al., 2005) who argued that roads (as part of urban infrastructure) are very critical and should be protected. While roads could be highly critical urban systems that aid inter-districting of crude-carrying tankers, they pose less stress on the ecosystem when impacted because they do not store sensitive hydrocarbons, hence the result.

ii. **Interdependence:** Also described as interconnectivity in previous investigations; is the assessment of the complexities upon which systems depend on each other for sustainable service delivery (R. Espada, Apan and McDougall, 2017). It is argued that understanding the consequences associated with complexity and evolving environmental regulations is crucial and could be used to define the criticality of such assets (Brown, Beyeler and Barton, 2004). Interdependence was used to judge the criticality of selected oil/gas infrastructure with the view that the more interconnected an infrastructure, the even more critical it is ranked as shown in ***Figure 27*** below:

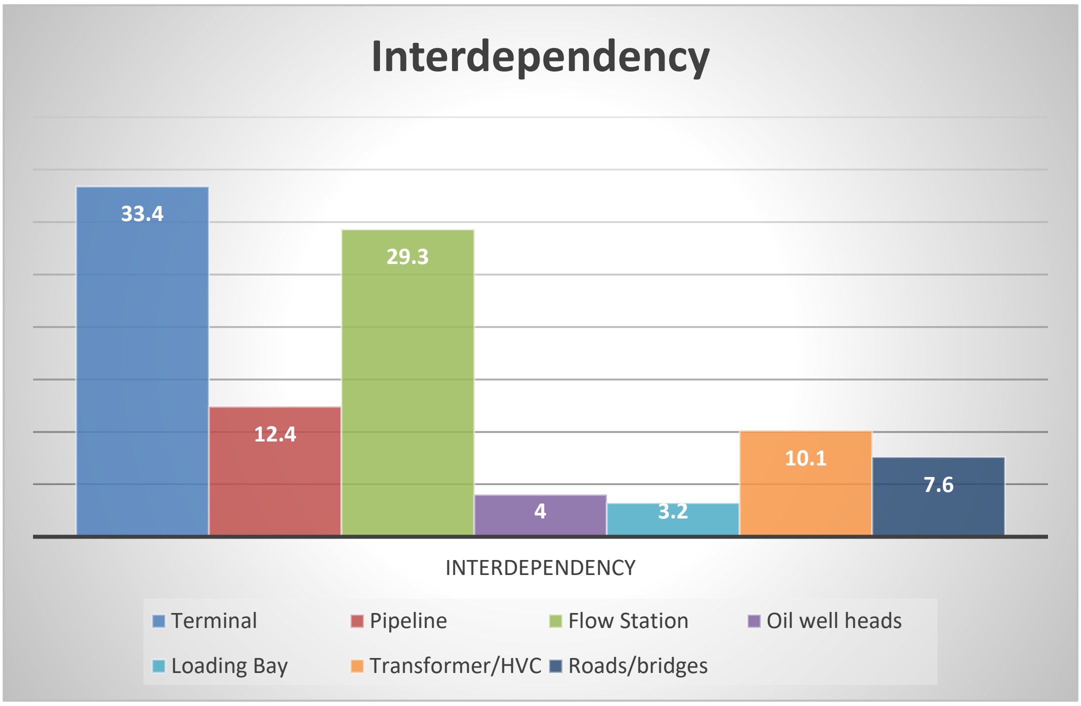

Figure 27 showing the criticality of infrastructure-based Impact on "Interdependence"

In the face-to-face elite interview, participants argued that *"…the most critical infrastructure among these is the terminal."* They argued further that "every operation ends in the terminal and until crude is delivered to the terminal, the operation is incomplete." Terminals receive crude from several flow stations through pipelines, making it highly interconnected and sensitive (El-Abbasy et al., 2015). Flow stations, on the other hand, are semi terminals serving as the first port for crude oil mixture from the wells. Depending on the number of wells, flow stations are usually connected to several wells powered by a high voltage of electricity and connected by roads and bridges; which might inform their judgement as indicated. Pipelines and transformers/HVC ranked 3rd and 4th respectively showing they are less interconnected while roads/bridges, wellheads and loading bays were ranked least in criticality due to interdependence in agreement with (Brown, Beyeler and Barton, 2004).

iii. Societal Relevance: societal relevance includes the environmental, social, and economic reliance on infrastructures for sustainable development. Infrastructure provides the society with the greatest sustainable development services such as water, food, energy, information, and crucial economic support for the government is considered critical (Fekete, 2011b). Societal relevance was used to assess the criticality of shortlisted oil/gas infrastructure with the result shown in *Figure 28* below:

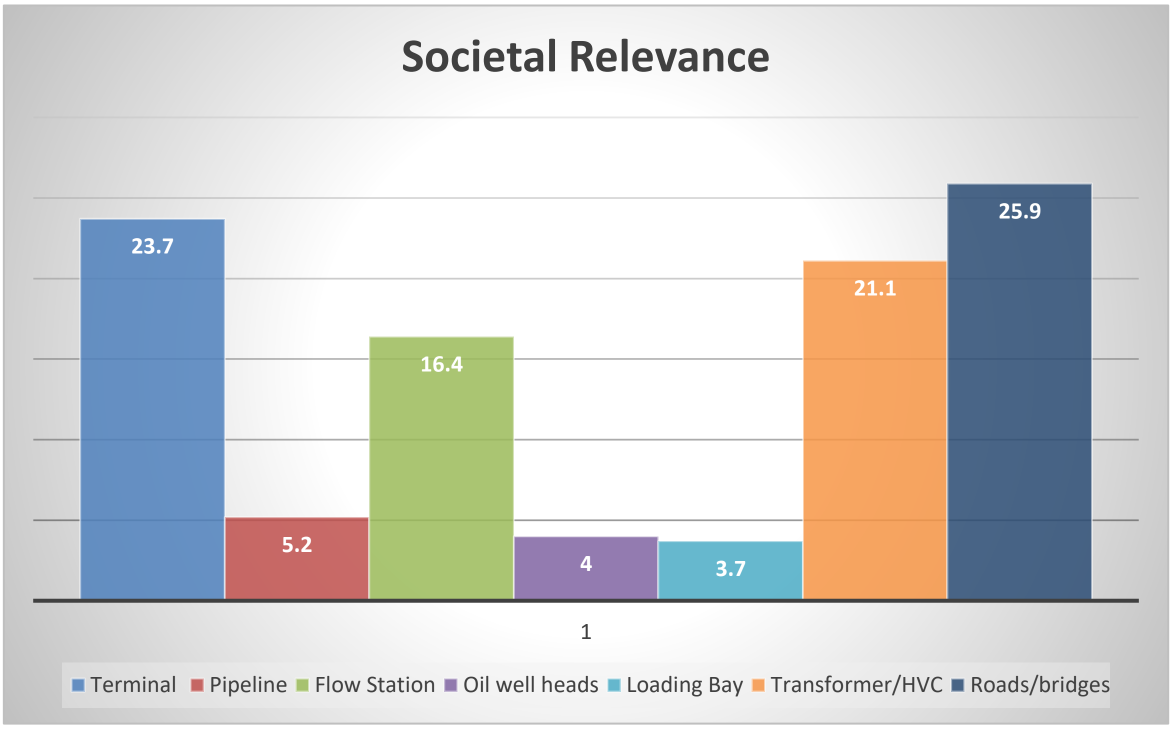

Figure 28 showing the criticality of infrastructure based on Societal Relevance

Roads/Bridges, terminals and transformer/HVC were ranked 1st, 2nd and 3rd in terms of their criticality due to societal relevance. This is because these systems provide the relevant economic and social needs of the society through transportation, power, and employment opportunities for professionals and artisans in the Niger Delta. It is contended that the impact on these systems could affect government revenue, reduce royalties and bonuses (Fekete, 2011b) which could have resulted in their high criticality ranking. Nevertheless, pipelines, wellheads and loading bays also played critical roles in the industry; usually when vandalised results in reduced oil production in Nigeria in the past. On this occasion, some assets such as transformers/HVC and bridges; were ranked higher because they are generally perceived as sensitive and fragile.

iv. **Impact on Human Health and Safety:** this is the consideration of various impacts such as pollution on human health and safety when infrastructures are impacted by climate burdens. Pollution and contamination of both air and ground resources by the oil spill had caused multiple impacts on human well-being (Singleton et al., 2016). Though the incidences such as the Deep-Water Horizon was a mechanical failure, the impacts of climate change on infrastructure could trigger similar effects resulting in a spill of toxic pollutants such as carbon (CO_2, CO, CH_4). Nitrogen oxides and volatile compounds hazardous to health could be spilt when critical infrastructures are impacted (Jafarinejad, 2017). The critical infrastructures in terms of impact on human health and safety in this study are shown below:

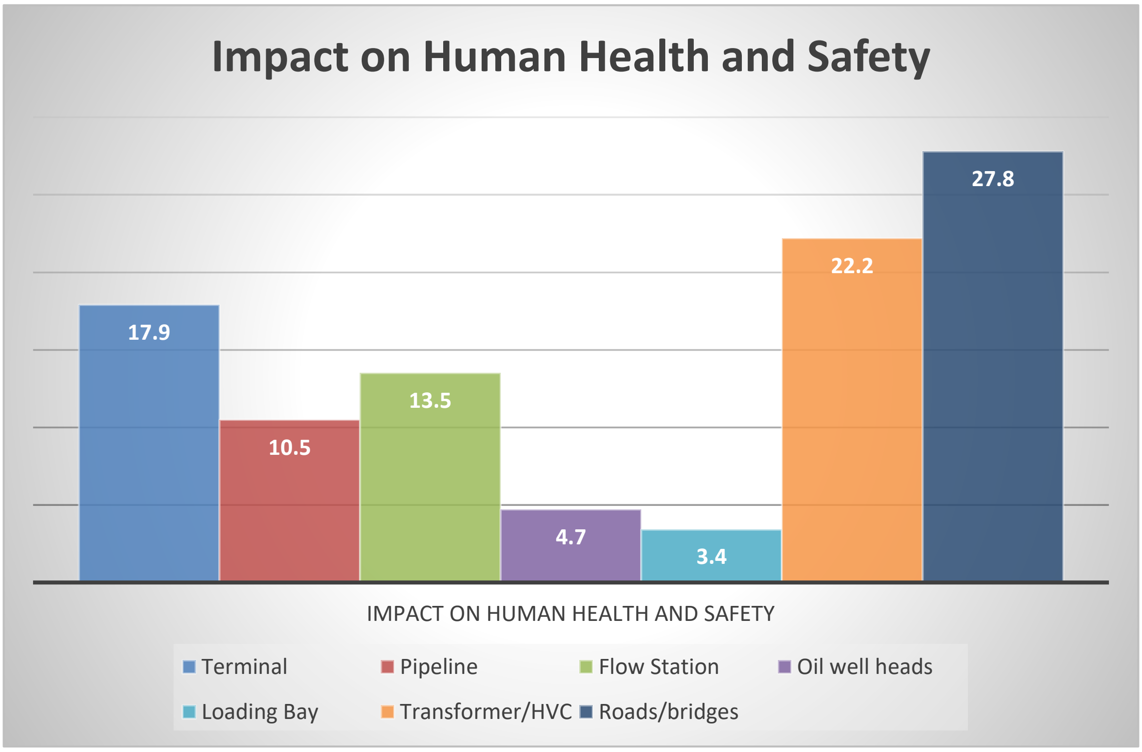

Figure 29; showing the criticality of infrastructure based on "impact on Human Health and Safety"

From the result above, roads/bridges and transformers/HVC are the most critical infrastructure, implying that if affected, could pose a severe impact on human health. This is contrary to expectations considering another outcome, which emphasises on terminals and flow stations. Relevant literature (Garg, Naswa and Shukla, 2014; Ra'ed and Keating, 2014; Straub, 2008; J. Moteff and Parfomak, 2004a) also suggests contrary that road/bridges or transformer/HVC could be ranked as most critical because they form part of daily transactional systems across industries. However, the interview revealed that *"…communities around OML 58 [oil mining lease] were most affected during the flood [in 2012] because access roads were also flooded, there was power outage …so they got trapped."* Nonetheless, as expected, the oil-bearing infrastructures are ranked 3rd, 4th and 5th respectively in agreement with available criticality arguments in the review (Verma et al., 2017; Haines et al., 2006). This is also because they are systems that aid the conveyance of oil/gas resources to domestic markets, hence played a critical role in the midstream sector.

v. **Availability of alternative:** this was used to assess infrastructure criticality based on the availability of a substitutional system when the primary systems failed due to climate change. The more readily available an alternative, the less critical the system to be impacted and vice versa (Adelekan, 2010). If a given infrastructure can be substituted timely and successfully, that could hasten the recovery and operational processes and reduce the burden of impact while contrary could exacerbate more stress, making the system crucial and critical. In this segment, the highly ranked infrastructure are less critical while the least ranked are more critical as shown below:

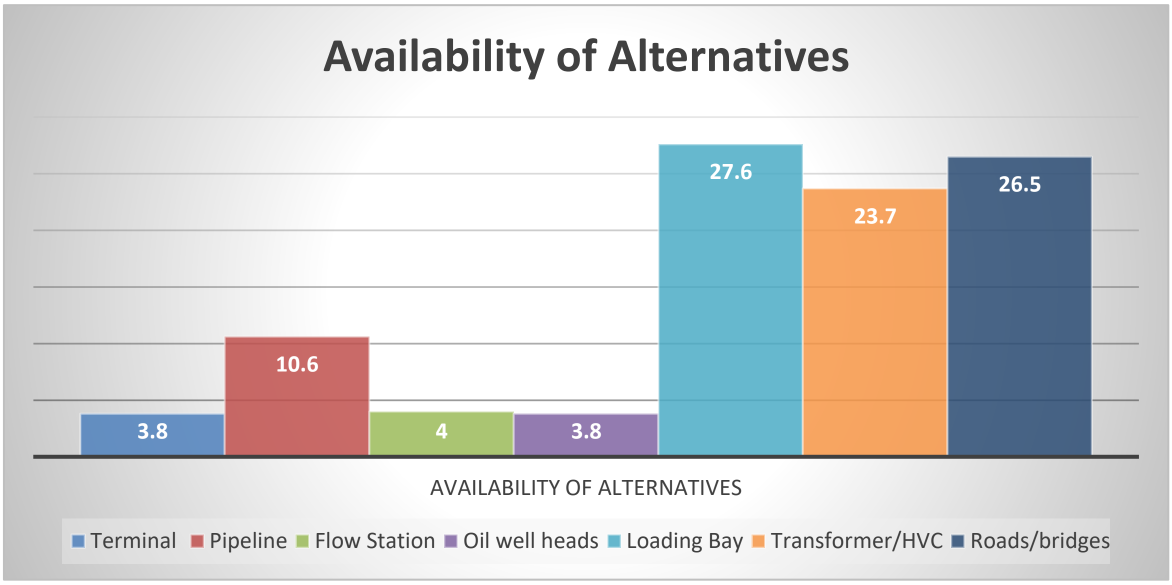

Figure 30 showing the criticality of infrastructure due to "Availability of alternatives"

From the result above, the most critical infrastructure are the oil wellheads, terminals, and pipelines with low availability of alternative score. The lower result for terminals, flow stations, oil wellheads and pipelines indicate that there are limited substitutional infrastructures to wellheads, terminals, and pipelines. Preliminary exploratory survey and observational investigation data agree with this result and revealed that these systems are crucial as they were seen to be highly guided and protected by 'burn walls' and 'lightning arrestors.' The result further agrees with relevant literature on infrastructure criticality evaluations that natural hazards play significant roles in triggering catastrophes on critical systems that lack immediate alternatives (Petrova, 2011).

vi. **The effectiveness of Alternative:** contends that while *"availability of alternatives"* may subsist, the effectiveness of the alternative(s) is also vital in measuring the criticality of an infrastructure. This is because an ineffective alternative measure could fail to mitigate an impact, hence exacerbate severe impacts on systems. An effective alternative is that which substitutes efficiently for a longer time and provides the resilience required for continual oil and gas exploration. In this study, infrastructures with the least or ineffective alternatives were ranked higher than those with probable significant effective substitutes (*Figure 31*).

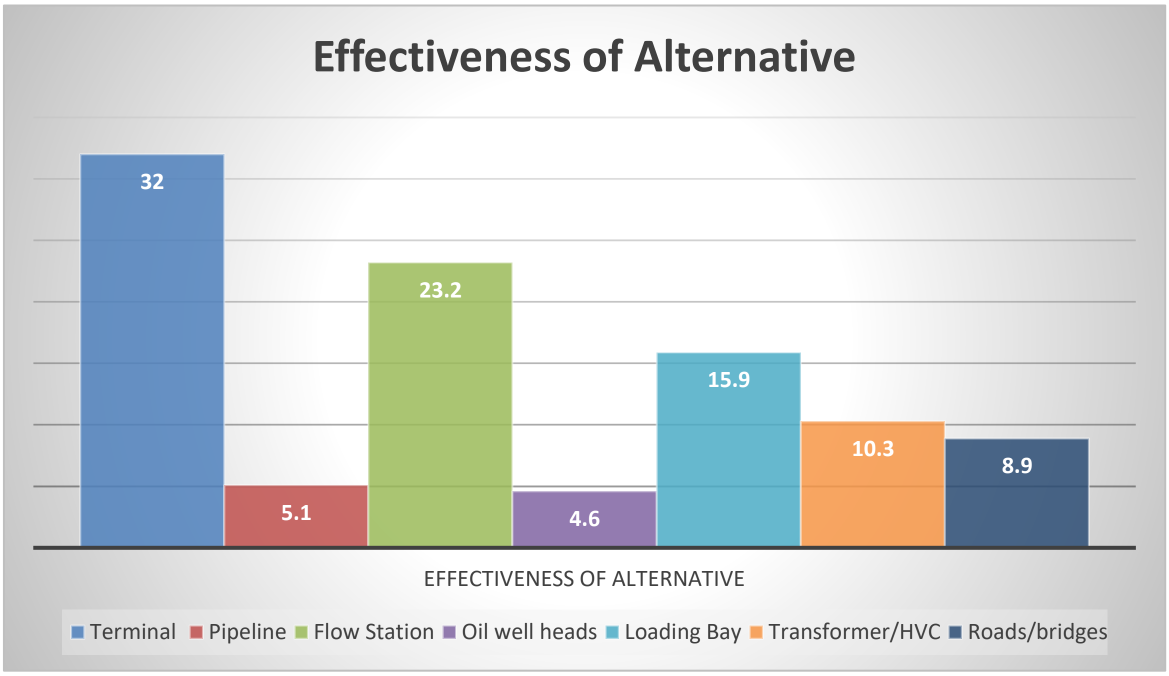

Figure 31 showing criticality ranking based on "Effectiveness of Alternative"

The result above indicates that terminals, flow stations and loading bays are the most critical infrastructure having been ranked 1st, 2nd and 3rd respectively, in terms of having effective alternatives. Aside from the interjection of loading bays, this result tallies with the outcome of *"availability of alternative"* in *Figure 31* by showing that infrastructure with the highest alternatives is the less likely to have an effective alternative. More so, results also show the loading bays being ranked high (27.6%) for "availability of alternatives" and relatively high "effectiveness of alternatives" (15.9%). This implies that though the alternatives are available for the loading bays, they are not effective, hence could still be classed as a critical infrastructure for vulnerability assessment.

Similarly, the pipelines and oil wellheads were ranked unexpectedly lower than all others. This implies that available alternatives to remediating systems for each of the infrastructures are ineffective. However, *Figure 31* shows that pipelines have a few available alternatives such as inland crude-carrying systems through rail or tankers which could be deployed to transport crude during climate-induced disasters' impacts on pipelines. Availability of alternative for the transportation of crude is in line with (Verma et al., 2017) argument that over recent years, oil production and associated issues have superseded pipelines crude transport in Canada. Their investigation proposed a rail transport model for effective delivery of 100,000 to 750,000 barrels of crude daily over 3000 km; which in effect completely transverses the length and breadth of the Niger Delta. However, a greater quantity of crude produced in the Niger Delta is transported by sea for export and domestic consumption is conveyed through roads across bridges but there are opportunities for rail services as an alternative, hence the result.

vii. **Cost of Replacement:** From the interviews, it was gathered that the severity of the 2012 flood impact in the Niger Delta caused a sudden rise in the insurance premium for some oil companies and other affected servicing companies (Ologunorisa, 2004). The *"cost of replacement"* was decomposed out of *economic niche* criterion from the literature review for ranking critical infrastructure because replacing damaged systems is capital intensive (Afieroho et al., 2017). The more capital intensive to replace systems, the higher the criticality ranking and implies in ***Figure 32*** that highly ranked infrastructure are more capital intensive to replace if impacted by climate change risks.

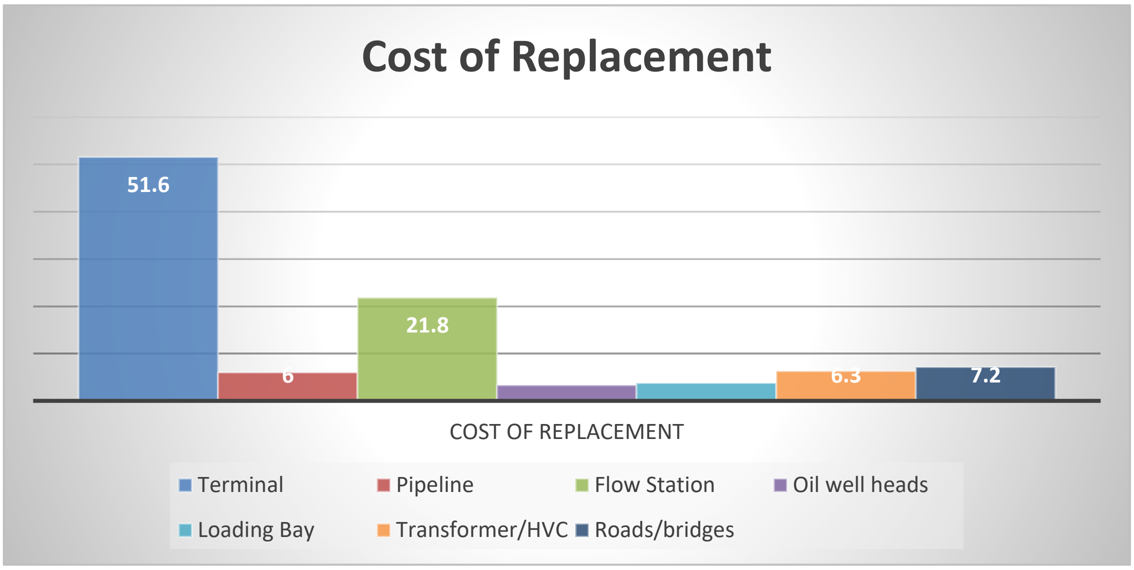

Figure 32 participants ranking based on the cost of replacement

As expected, the result indicates that the terminals have a very high cost of replacement taking close to 52% of the entire AHP score and ranking first. This is because terminals are very crucial and perennial almost irreplaceable infrastructures in the industry. The outcome of this study agrees with both exploratory and observational findings, which revealed the sensitivity of the systems and protection around terminals. More so, terminals are final destinations of crude oil and gas from where exports are made through crude-carrying vessels or to refineries for processing.

The result further shows that flow stations could also involve the high cost of replacement. Flow stations are the first ports of separation of crude oil from water. In a face-to-face interview, it was gathered that flow stations are also the perennial infrastructures that are built with the consideration of associated reservoir capacity and calculated production peaks for every inter-connected oil well. Several reservoirs are connected to flow stations and according to one of the respondents, *"…except there is an unexpected result not matching reservoir performance"* or impacts, this interconnectivity is sustained over a long period of time.

The balance of infrastructure shows the very low cost of replacement, which also presents a level of judging their criticality with respect to this criterion. Summarily, the result shows that terminals are the highest (51.6%) critical infrastructure and twice higher than flow stations (21.8%) due to cost of replacement and agrees with (Afieroho et al., 2017) that replacing or decommissioning critical infrastructure in the industry is capital intensive.

6.2.10 Analysis of Consolidated Ranking Result

Individual comparisons were consolidated from normalised eigenvalues (

Table 911) to produce the overall aggregate ranking for criticality. The result shows the criticality of each of the seven alternatives (infrastructure) according to the assessment criteria and indicates that the three most critical infrastructure are; Terminal (27%), Flow station (19%), and Roads/bridges (15%). Others are Transformers/HVC (14%), while Pipelines, loading bays and oil/gas Wellheads obtained 11%, 9%, and 5% respectively and ranked 5th, 6th and 7th as shown in *Figure 33* below.

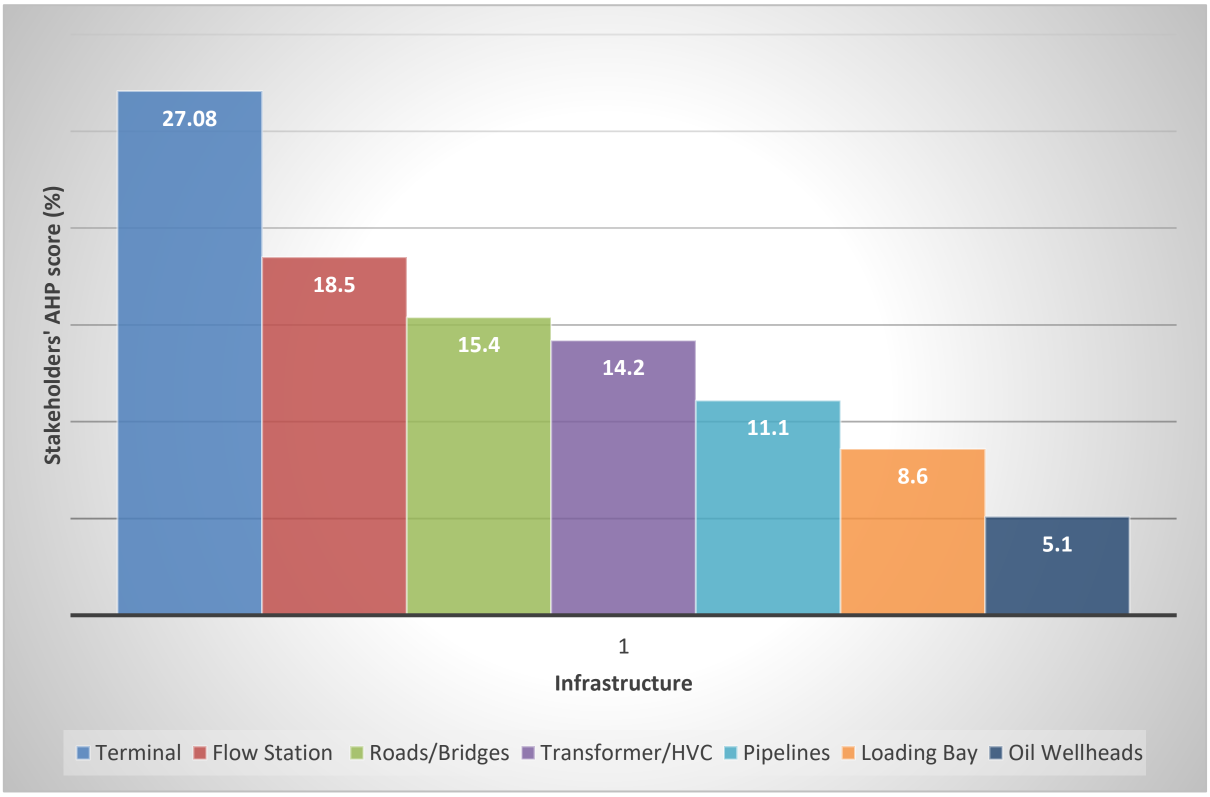

Figure 33 Aggregated result of participant's priorities using the Analytic Hierarchy Process for measuring criticality of selected infrastructure in the Niger Delta

From this study, *oil/gas terminal*, *flow station* and *roads/bridges* are considered as the most critical infrastructures in the Niger Delta and imply that in the event of climate change disaster such as flood, storm, etc; attention should be given to these systems in their order of priority. It further suggests that damages to these systems would significantly impact on the criteria with the highest ranking in the criteria ranking in

Table 9. For a more elaborate analysis, the impact of climate change on a crude oil terminal (QIT or Escravos for instance) could cause cascading impacts on ecosystems, human health and the general society where economic relevance is crucial. This result agrees with the postulation of Haines et al (2006); Beg et al (2002); Adelekan (2010); and Burkett et al (2008) who claimed that climate change could cause a huge impact on sustainable development, with significant effects on ecosystems, human population, and social balances of communities in vulnerable coastal areas.

Interdependence could also be significantly affected if climate change impact on the terminals (27.1%), flow stations (18.5%) or roads and bridges (15.4%) in order of their weights. The terminal is adjudged most critical infrastructure because it forms the ground for storage and loading of crude oil/gas resources for export and domestic consumption. The Quo Iboe

Terminal (QIT) and Escravos in the Niger Delta are examples of this critical asset interconnected with varied sizes (12" – 30" inches) of trunk lines, delivery, and export pipelines. These pipelines, which transport crude oil from wellheads through the flow stations, form a network of interdependent systems sensitive to climate impacts directly or indirectly along the system value chain. The terminal, flow stations, roads and bridges, electric transformers and HVC, pipelines, loading bay and oil wells are multimillion dollar systems which because of the relevance of crude oil to the economy, have become critical national assets (Forzieri et al., 2018; Ackerman and Stanton, 2006; Kemfert and Schumacher, 2005). Unfortunately, these critical infrastructures are in the Atlantic coast where climate burdens such as coastal storms, rising tides and sea level, frequent and heavy downpours, flooding and corrosion are expected to exacerbate different levels of impacts.

Given these climatic threats, there is a need to investigate further the vulnerability of these critical infrastructures to climate change in the Niger Delta. The next section focuses on the vulnerability assessment to evaluate the most vulnerable systems based on specific indicators.

6.3 VULNERABILITY ANALYSIS

In section 6.2, the analysis focuses on the criticality of infrastructures. The essence of criticality assessment was to identify by ranking selected oil/gas infrastructure in order of their priority from participant's viewpoints. The outcome paved the way for vulnerability assessment of the critical infrastructure to climate change using impacts-based criteria from the systematic review. This aimed to achieve the major objective of the study and justify the framework of the investigation.

The analysis in this section also combines the data from the focus group (AHP) with transcribed semi-structured qualitative interview data simultaneously. The essence of this simultaneous analysis is to further elucidate and strengthen analytical logic and critically illuminate the vulnerability of these infrastructures from both Management and Field Engineer's perspectives. It further presents a more robust, understandable, and tangible argument on the vulnerability in the Niger Delta.

The AHP focus group data is analysed using the multiple input (Mi) spreadsheets to determine participants' priorities of selected alternatives (infrastructure) in their order of vulnerability. The main output of this section addresses the research question; "which are the vulnerable critical oil and gas infrastructure in Niger Delta?" It also shows clearer evidence of vulnerable alternatives from multi-criteria decision-making analysis (MCDM) pathway and shows the various burdens of climate change. Like the case of criticality outcome, vulnerability assessment presents the first-hand database on susceptible assets to climate change burdens in the Niger Delta oil and gas industry. These findings eliminate the bottlenecks involved in identifying suitable adaptation mechanisms for the industry against vulnerabilities. It further presents a strategic and systematic multi-stakeholder approach for prioritising infrastructure for adaptation to climate change-induced disasters which agrees with existing research (Füssel, 2007; Rutherford, Hills and Le Tissier, 2016). This study aims to produce a hierarchical asset template suitable for global adaptation planning for oil/gas assets against climate risks such as rising oceanic tides and sea level, increasing temperature, flood risks, coastal storms, and heavy downpours.

6.3.1 Vulnerability Assessment procedure

This section presents a procedural analytic pathway of assessment consisting of; the goal of assessment, a ranking of the criteria, and comparison of alternatives (*infrastructure)*.

6.3.2 Criteria and Infrastructure

Table 12 below presents criteria and infrastructure that are assessed for vulnerability. Special pre-assessment training was conducted for participants by re-defining the criteria and how they were applied to judge and complete the AHP questionnaire.

Table 12 Criteria and infrastructure for vulnerability assessment

S/N	Criteria	Infrastructure
1	Exposure	Oilwell
2	Adaptive capacity	Pipelines
3	Proximity	Flow stations
4	Presence of climate burdens	Oil terminals
5	Criticality	Loading bay
6	Age of infrastructure	Roads/bridges
7	Interdependence	Transformer and HVC

Step 1 Determination of Assessment Goal: the goal of this section of assessment is to evaluate the vulnerability of critical oil/gas infrastructure to climate change impact.

Step 2 Pairwise Comparison and Ranking of the Criteria: In this step, the seven (7) criteria in Table 12 were pairwise compared by participants to determine their specific weights. Their responses were independently keyed into nineteen (19) Mi-AHP spreadsheets. The justification for comparing the criteria was to determine how each criterion weight would contribute to the vulnerability of alternatives in the overall study. A demonstration of the pairwise comparison matrix is shown in figure Figure 34. The white upper section indicates participants' entries using the Saaty (2001a) numerical scale (1, 3, 5, 7, 9) in comparing any two criteria while the grey section shows the reciprocal of the entries.

Matrix		Exposure 1	Presence of Burdens 2	Criticality 3	Proximity 4	Adaptive Capacity 5	Age of Infrastructure 6	Interdependence 7	Normalised principal Eigenvector
Exposure	1	1	3	5	1	5	3	1	27.47%
Presence of Burdens	2	1/3	1	1	1	3	3	3	17.09%
Criticality	3	1/5	1	1	1	3	3	1	12.61%
Proximity	4	1	1	1	1	5	5	1	17.92%
Adaptive Capacity	5	1/5	1/3	1/3	1/5	1	1/3	1/3	3.88%
Age of Infrastructur	6	1/3	1/3	1/3	1/5	3	1	1/5	5.59%
Interdependence	7	1	1/3	1	1	3	5	1	15.43%

Figure 34 showing the comparison matrix and normalised principal Eigenvectors

Step 3; Analysis of criteria ranking outcome

The individual judgements were consolidated (aggregated) and normalised to produce the normalised eigenvectors shown on the right column of Figure 34 and appendix XXI. The result indicates that '*Exposure*' is the highly weighted and significant criterion (27.5%) in the assessment after *proximity* (17.9%) and *presence of burdens* (17.1%) while *interdependence* and *criticality* obtained 15.4% and 12.6% respectively. *Age of infrastructure* (5.6%) and *Adaptive capacity* (3.9%) were the lists of significant criteria. Resultant weights (yellow column) and ranking (green column) of each criterion from the matrix above are presented in Figure 35 below for transparency and easy readership.

Criterion		Comment	Weights	Rk
1	Exposure		27.5%	1
2	Presence of Burd		17.1%	3
3	Criticality		12.6%	5
4	Proximity		17.9%	2
5	Adaptive Capacity		3.9%	7
6	Age of Infrastruct		5.6%	6
7	Interdependence		15.4%	4

Figure 35 showing the resultant weights and rankings of vulnerability assessment criteria

Step 4: Pairwise Comparison and ranking of infrastructures

This step presents the systematic criterion-by-criterion pairwise comparisons of the seven infrastructures (alternatives) and determines the level of vulnerability based on each criterion's independent assessment threshold. To achieve this, responses from the nineteen participants were consolidated using the Goepel (2013a) Mi-AHP spreadsheets and the analysis illuminates vulnerable critical infrastructure. Figure 36 shows the systematic comparison pathway from level 1; goal determination to level 2; comparing the criterion to ascertaining their given weights in the investigation and to level 3; the pairwise comparison of infrastructures.

In level 1, the values of weight of each criterion are indicated to show which has greater influence in the vulnerability outcome. Similarly, the values and extent of vulnerability of each infrastructure from the analysis are also indicated. The higher values indicate high vulnerability.

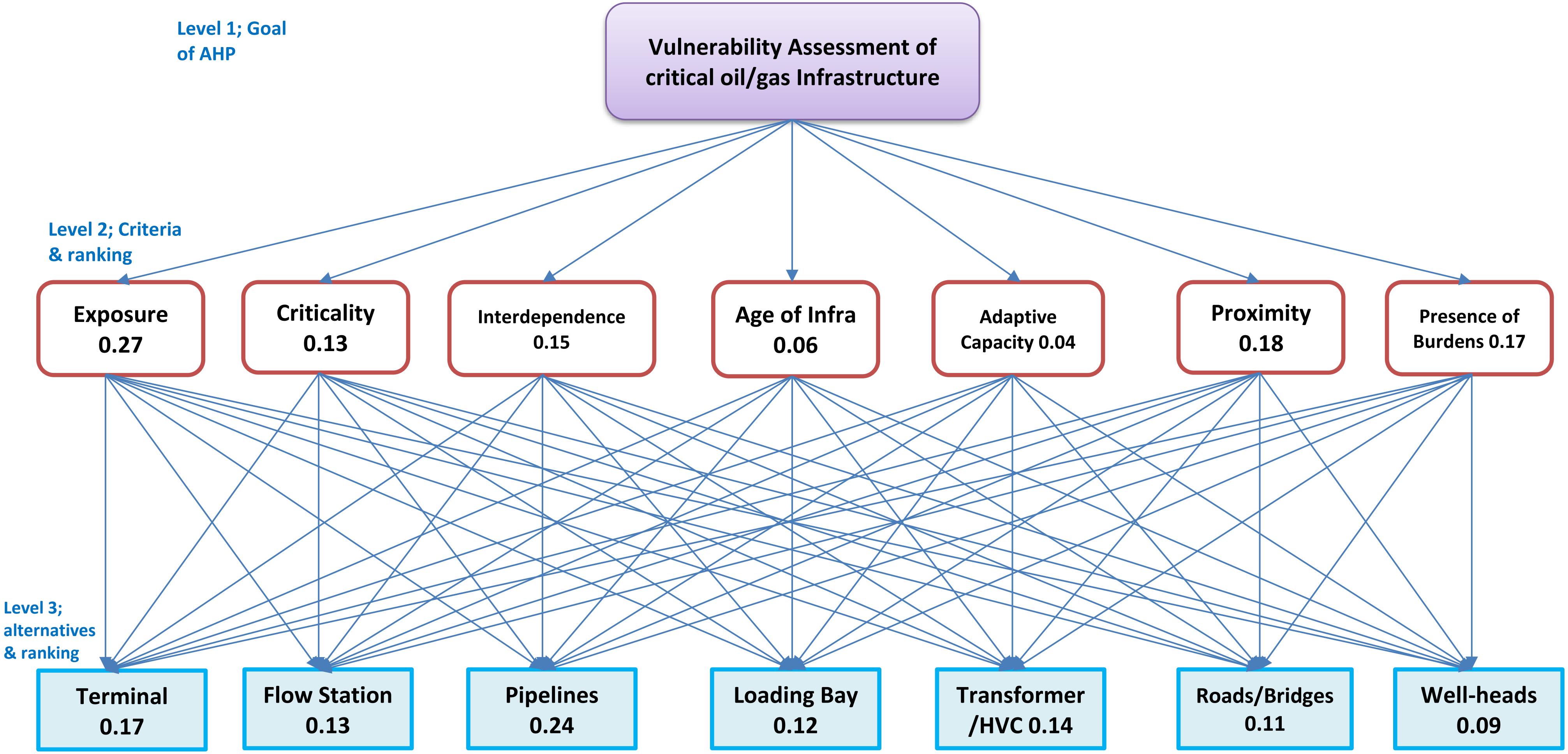

Figure 36 Vulnerability pairwise comparison pathway using Analytic Hierarchy process model

6.3.3 Description of Mi-spreadsheet mechanism

Like criticality analysis, responses from participants were carefully transferred from questionnaires into seven (7) Mi-AHP spreadsheets (according to 7 criteria of assessment). For each criterion, nineteen worksheets (light green) shown horizontally as In1, In2, In3…In19 in Figure 37 were created for the 19 participant's data input, hence the name *multiple inputs* (Mi-AHP). A summary sheet (blue cell) automatically aggregates the data inputs from 19 sheets and present the consolidated hierarchies of vulnerability for a given criterion.

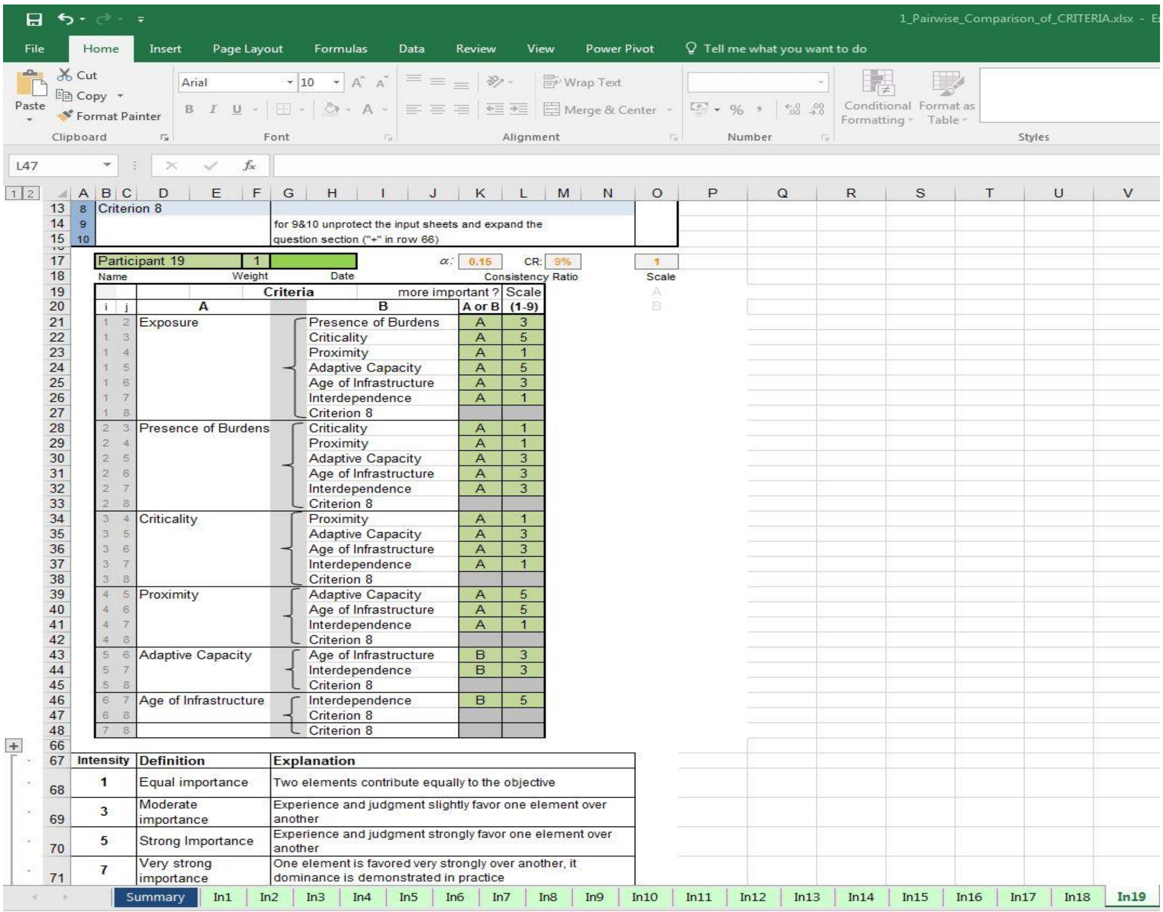

Figure 37 showing the summary sheet and nineteen individual participants sheets (In1 -In19)

6.3.4 Brief Description of Ranking Process

Participants applied each criterion in level 2 (Figure 36) to pairwise compare the seven alternatives in a matrix system (see a demonstration with blue lines). Twenty-one (21) possible sets of separate pairwise comparisons were involved in the matrix process. Consolidated results from the Mi-spreadsheets are exported and shown in Table 13.

The table shows criteria (horizontal row) and infrastructure (vertical columns) to demonstrate criterion – by - infrastructure ranking matrix. The pairwise comparison shows that for each criterion, a 100% score is distributed amongst seven critical infrastructures according to their percentage of vulnerability. More so, each 'cell' in the table is an aggregation of nineteen (19) individual decisions from the focus groups. The blue column (right of table) shows criteria '*total row score'* for each critical infrastructure and sum up to 700. This is divided by 100 to obtain the normalised eigenvalues percentages (shown in the purple column). These can be further normalised to '1' using row geometric mean method (RGMM) to obtain geometric mean values by dividing each value by 100. Successful normalisation (= 1) is an indication of the accuracy and validity of assessment. This agrees with existing analytic hierarchy process involving multi-stakeholder pairwise comparison investigations for vulnerability assessments (Jagtap and Bewoor, 2017; Z. Xu, 2000; Saaty, 2001b; Zimmerman, 2004a; Al-Harbi, 2001).

6.3.5 Analysis of Consistency Ratio (CR)

In Table 13, the orange column shows aggregated consistency ratios (CR) and a consensus outcome for each criterion ranking. These weights were consolidated by row geometric mean method (RGMM) from individual criterion assessment (Xu, 2000). Overall CR outcome for vulnerability assessment is *9%* as opposed to the margins proposed from the literature and methodology – placing CR at 0.1 and 0.15 with an error margin of +/-0.2. This result indicates that participants were consistent in the decision-making process in comparing the infrastructures, which agrees with Saaty (2003); Xu (2000). CR outcome also indicates that participants selected for this study were suitably stratified and understood the pairwise process. It further validates the effectiveness of the research framework implemented through AHP agrees with Xu (2000), Al-Harbi (2001), and Saaty (2001b) who argued that appropriate framework implemented through AHP could produce a valid research result.

Table 13; consolidated result computed from AHP Excel spreadsheet on the vulnerability of critical infrastructure

	RESULT FROM AHP RANKING OF MOST VULNERABLE CRITICAL INFRASTRUCTURE								
Criteria Alternatives (infrastructure)	**ADAPTIVE CAPACITY**	**AGE OF INFRASTRUCTURE**	**INTERDEPENDENCE**	**PRESENCE OF BURDENS**	**EXPOSURE**	**CRITICALITY**	**PROXIMITY**	**TOTAL SCORE**	**NORMALISE EV VALUES (%)**
TERMINAL	6.1	11.4	34	18.3	17.3	19.4	12.4	**118.9**	**16.9**
FLOW STATION	6.1	13.4	10.5	11.2	6.8	28.8	10	**86.8**	**12.5**
PIPELINES	23.2	27	16.9	36	25.3	19.2	25.1	**172.7**	**24.7**
LOADING BAYS	23.4	5.8	4.4	4.4	20.3	3.8	20	**82.1**	**11.7**
ROADS/BRIDGES	12.1	17.5	17.3	15.6	12	11.1	13.4	**99**	**14.1**
TRANSFORMERS/HVC	9.5	10.9	11.6	9.7	12.1	10.5	11.8	**76.1**	**10.9**
OIL WELLHEADS	19.6	14	5.3	4.8	6.2	7.2	7.3	**64.4**	**9.2**
AGGREGATE SCORE	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**700**	**100**
CONSISTENCY RATIO	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**9.1**	**0.09**
CONSENSUS LEVEL	**71**	**71.7**	**78.5**	**73.3**	**66.9**	**77.6**	**62.4**	**501.4**	**71.6**

6.3.6 Analysis of Consensus

A high CR is expected to yield a high consensus outcome from the same study (Dong et al., 2010). In this study, a consensus of 71.6% was recorded. This implies that there was about 72% unanimous and objective agreement between participants in the independent group decision-making and judgement. This result agrees with the position of Dong et al (2010) who posits that though the absolute consensus is not expected for empirical application of AHP, a high consistency ratio could result in a high consensus degree indicating high validity of the result. This also indicates a high level of success in interdisciplinary judgement and intersecting acceptance of vulnerability outcome. It is contended that a low consensus level implies that alternatives models such as geometric means, individual voting, and compromise models could be implemented for further evaluation (V. S. Lai, Wong and Cheung, 2002). But this outcome negates the need for a further test of exclusive alternative approaches coupled with the synthesis in Mi-AHP spreadsheets presented as normalised Eigenvectors. This ultimately substantiates high consensus outcome and justify the suitability of AHP for multi-stakeholder decision-making.

6.3.7 Criterion-by-criterion analysis

To criticality underpin the vulnerabilities according to applied indicators in the assessment, a criterion-by-criterion analysis is conducted (See appendix XXII – XXVIII). It illuminates the reasons for each criterion in ranking and the outcome of the seven (7) critical oil/gas infrastructure.

a) Adaptive Capacity: this is the ability of infrastructure to withstand a certain level of climate impact magnitude or stress (Smit and Wandel, 2006). If any infrastructure located in a climate risk-prone area has a weak capacity to withstand a certain magnitude of climate stress (example flood), it is adjudged as vulnerable. This threshold was used by participants to compare seven critical infrastructures for vulnerability assessment using the AHP matrix principle. Normalised principal ranks (eigenvector) result from the matrix is shown in *Figure 38* below.

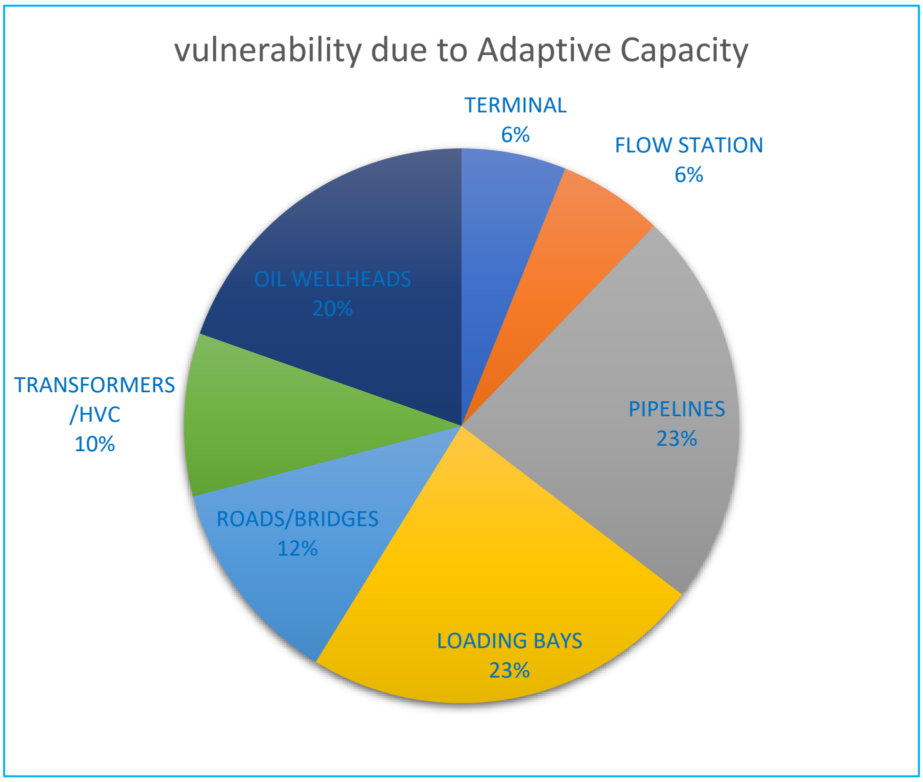

Figure 38 Showing percentage of the vulnerability of infrastructure due to adaptive capacity

From figure 39 above, normalised principal eigenvectors show vulnerability percentage for infrastructure based *adaptive capacity (ac)*. The result indicates that pipelines and loading bay are the most vulnerable. This implies that pipelines, loading bays and wellheads lack the resilience and resistance to withstand climate stress in the Niger Delta. It implies that climate risks were probably not captured at the construction and fabrication stage of the most vulnerable system where adaptive capacities were not built into the infrastructure lifespan. From the result, terminal and flow stations are said to be the least vulnerable infrastructure in terms of adaptive capacity. This outcome corroborates with the criticality assessment result where oil/gas terminals and flow stations were judged as the most critical, hence expected to receive more attention in terms of routine maintenance and repairs. In a separate interview with an Assets Manager, it was revealed that the terminal is the *"eye of oil/gas production and transport chain."* Its niche should make the systems highly sensitive and attractive to management adaptation plans for constant protection from all environmental and human-induced forces such as vandalism.

b). Age of infrastructure: also considered as obsolescence is an appraisal of a system's performance due to its lifespan from the date of installation. The older an infrastructure, the weaker it becomes with significant wear that could make it vulnerable to climate change impacts (Karapetrou, Fotopoulou and Pitilakis, 2017). Ageing effect on sensitive systems compromises their dysfunctional capability, mechanical inefficiency and reduced profitability at any minor environmental stress (Sørensen and Stuart, 2000).

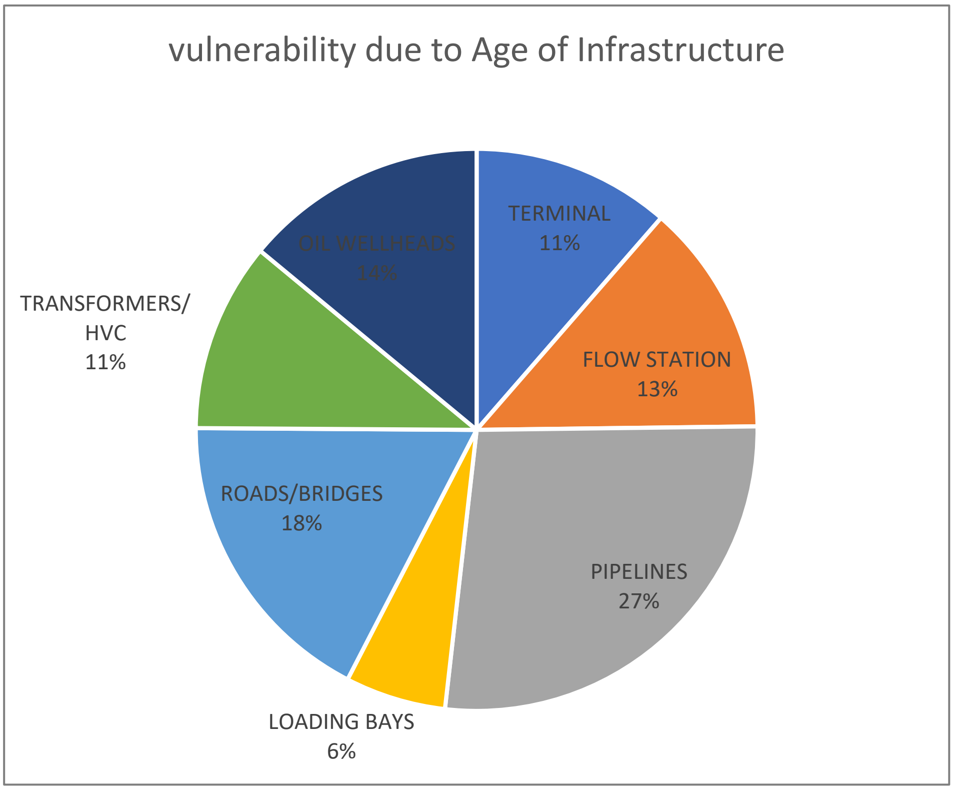

Figure 39 showing percentage of vulnerability due to "Age of infrastructure"

Figure 39 shows that *pipelines* are the most vulnerable critical systems (by 27%) and closely followed by *roads and bridges* (rated 18%) according to obsolescence, age or outdatedness. However, this contradicts the response of the interview respondents who claimed that pipelines are constantly being replaced due to regular vandalism orchestrated by the actions of militants. Constant replacement of pipeline infrastructure implies that they are often not allowed to live their design life or attain obsolescence stage before premature replacement. But it could be argued that vandalisation of pipelines is often not comprehensive and substantial enough to cause a holistic replacement across the systems value chain. In a separate interview, a respondent argued further that:

"...some pipelines have been there for over fifty years which we can now consider mature for replacement or decommissioning..."

Another interview participant contended *that "...newly installed infrastructure could still be vulnerable to flood, corrosion, and ocean tides..."* if located in inundated coastal areas as in the case of the Niger Delta. This implies that this outcome is valid as there is no direct relationship between premature replacement of systems and its vulnerability to climate impacts.

From exploratory fieldwork, it is gathered that the roads to platforms and location of infrastructure are in deplorable conditions. Figure 39 presents a direct interpretation of vulnerability of roads and bridges to flood and other climate burdens in the Niger Delta. More evidence from the exploratory survey is the high records of collapsing inter-districting oil tanker around the Niger Delta road/bridge network, leading to the secondary land-based oil spill and environmental pollution (Kadafa, 2012; Ajao and Anurigwo, 2002). The *loading bay* (6%), transformer/HVC and *terminal* (11%), ranked least in terms of age while oil *wellheads* and *flow stations* occupied the intermediary ranks with 14% and 13% respectively. These systems are interconnected in the infrastructure value chain and could be jointly affected if any aspect of the linkages is impacted.

c). Interdependence: is the measure of interconnectivity and linkages that exist between critical infrastructures. It is expected that due to linkages, an impact in one could trigger a chain of impacts on all other linked systems, hence exacerbate levels of vulnerability (Zimmerman, 2004a). *Figure 40*0 shows the vulnerability of critical infrastructures to climate change impacts due to *'interdependence'* where terminals are the most vulnerable (34%) while roads/bridges and pipelines are 2nd with 17% vulnerability levels each. This is because all other infrastructures (pipelines, roads, electric cables, and transformers, etc) are linked to the terminals such that impact on any could affect the terminals. Example include any disruption along roads/bridges and pipelines networks, which are well interconnected across the systems. The result further indicates that the least interlinked infrastructures are the least ranked systems in terms of vulnerability (Zimmerman, 2004a). This implies that systems that are densely interlinked are more vulnerable to climate change impacts and should be given due consideration in terms of adaptation planning.

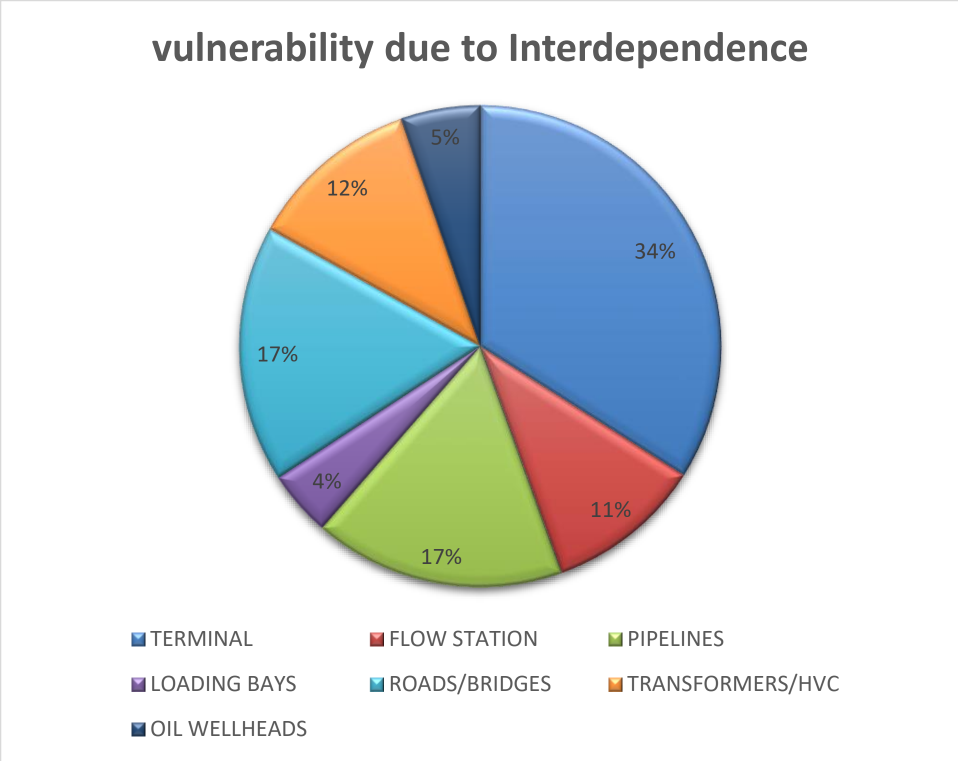

Figure 40 showing the percentage of vulnerability due to "Interdependence"

d. Presence of burdens: the presence of burdens describes the existence of climate change impacts in the study area. The argument of *'presence of burdens'* or risk evolves from the mix that it is the presence of risk around an infrastructure that defines vulnerability. This view conforms with the argument that vulnerability can only be measured by a specific hazard present in each geographical location (Brooks, 2003).

From *Figure 41*1, the vulnerability due to the presence of burdens indicates that pipelines are most vulnerable to existing climate change burdens in the Niger Delta with a score of 36%. This is because pipelines spread over hundreds of kilometres across inundated floodable landscapes and are exposed to direct heat and suffer different degrees of corrosion, wear, and tear in the Niger Delta. Those buried underneath the ground are also at risk of geomorphological shifts and tectonic movement. These are further exacerbated by Atlantic tidal effects, denudation, and continual exfoliation of rocky protections (Okuno et al., 2014). They found that crustal movement in the Japanese coastal region, through multi timescale modelling of sea level rise, impact on critical systems. This further justifies the outcome of this study which shows that the dominance of climate burden could have severe effects on both isolated and linked systems.

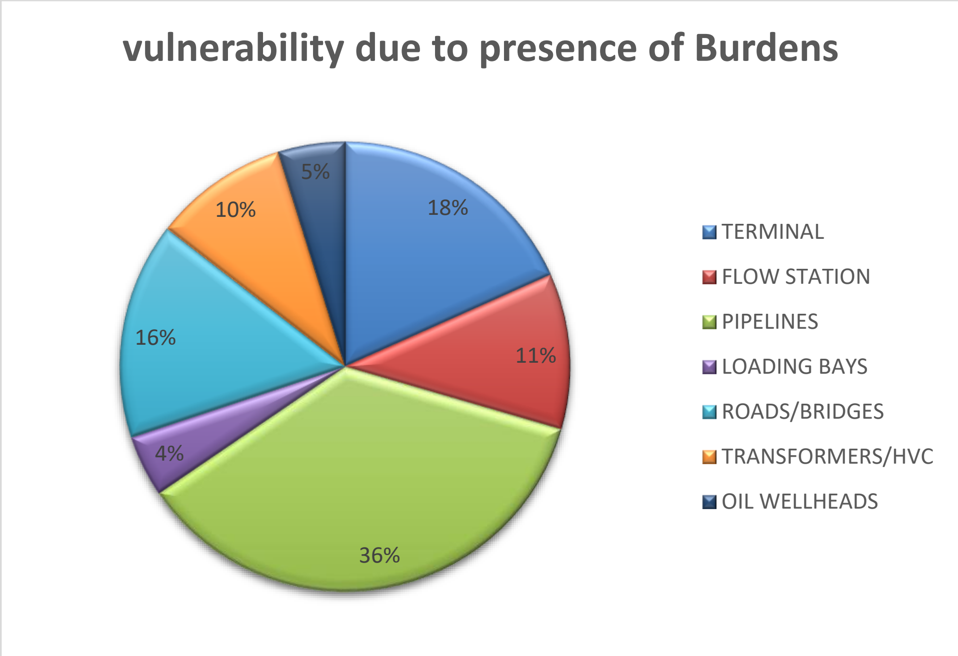

Figure 41 showing percentage of vulnerability due to "Presence of burdens"

However, terminals and roads/bridges were ranked 2nd and 3rd while transformers/HVC and flow stations were ranked 4th and 5th in vulnerability to burdens. Oil wellheads and loading bays ranked 6th and 7th; probably because these systems are not widespread in the region to be affected by the overlapping existing burdens. For instance, the pipelines, terminals, and roads/ bridges ranked high because of ubiquity and sensitivity compared with wellheads that are in situ and occupies a limited amount of space.

e. Exposure: is the susceptibility of systems to climate change hazards. It is also the exposure of systems to frequent and duration of rainfall, flood, heat, and storms, etc with the capacity to impact on their performance and function (Cardona et al., 2012; Correa and Yusta, 2014; Espada, Apan and McDougall, 2017).

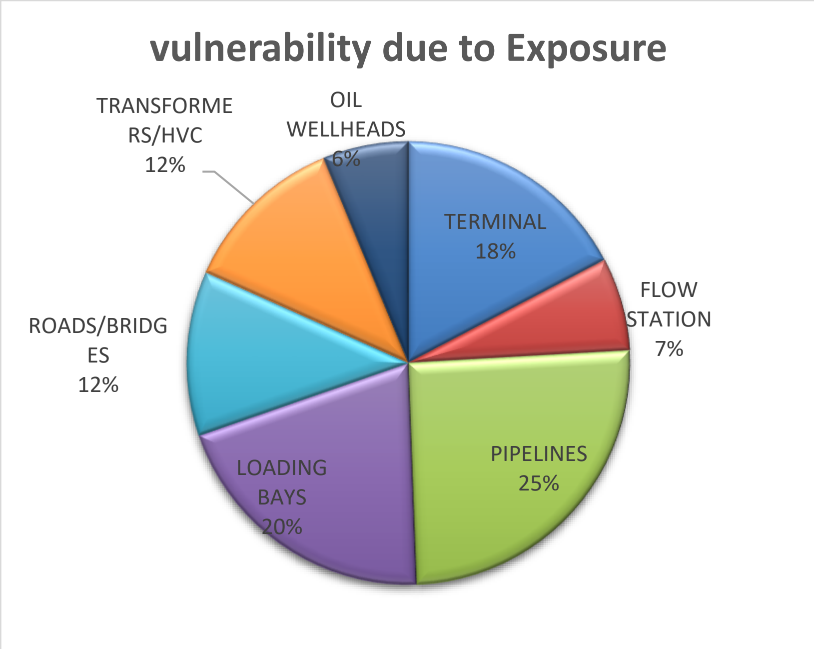

Figure 42 Showing percentage of vulnerability due to "Exposure"

Figure 42 shows the level of vulnerability due to *exposure* to infrastructure. Unlike *'presence of burdens'*, there is a fairly even distribution of vulnerability among the systems due to exposure. However, pipelines maintain a high vulnerability (25%) while loading bays occupy the 2nd level with 20% of exposure. Generally, infrastructure within a location such as the Niger Delta with uniform climatic threats are expected to have equal levels of exposure as indicated in the result but some hierarchies are observed. This is because some assets could be exposed to multiple and severe degrees of climate threats, hence ranked slightly more than others as shown. Wellheads and flow stations are ranked 6th and 7th as the least exposed system probably because of the influence of location as most of the flow stations are installed on elevated platforms. It was observed from field investigation that systems located on elevated platforms were not impacted as others on low elevation during the 2012 flood in the Niger Delta. More so, Asset Managers disclosed that flow stations are constantly monitored and adapted to ensure that they performed at maximum operational capacity. This implies that the construction of higher elevations for assets installation is a possible adaptation mechanism for critical oil and gas infrastructure in the Niger Delta.

f. Criticality: has been defined as the degree of sensitivity of a system to the society, organisation or agencies; where its destruction could cause an enormous impact on the economy, policy, security, lives and public health and safety (Ra'ed and Keating, 2014; Theoharidou, Kotzanikolaou and Gritzalis, 2010a; Moteff and Parfomak, 2004a). It is argued that climate change threats such as the floods, wind storms and rising temperature has the capacity to cause a maximum degree of destruction of critical oil and gas infrastructure (Nature, 2017).

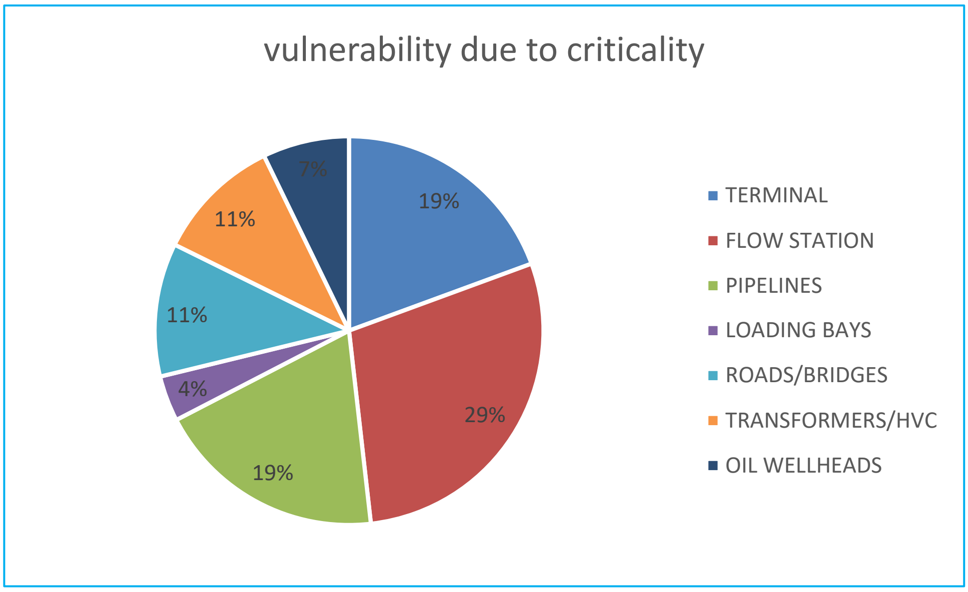

Figure 43 showing percentage of vulnerability due to the criticality of infrastructure

The result above indicates that flow stations are highly vulnerable in terms of *criticality*. This is expected because flow stations are hotspots infrastructure where crude oil from the wellheads is first separated from water before further transportation to the terminals. Because of this crucial activity, flow stations are considered as a sensitive system that requires maximum protection from impacts of climate-induced disasters.

Several wellheads are connected to flow stations that make it attractive to facility managers across the industry to prevent an oil spill. An impact of climate hazards on flow stations, terminals, and pipelines (ranked 1st 2nd and 3rd in Figure 433) could cause oil spill which could cascade through to posing a severe impact on human lives, ecosystems, as well as affects the PEAR operational ethos of the companies. As expected, the loading bays though perform a critical role in the value chain but are not sensitive systems because alternative crude oil loading access into Crude Carrying Vessels (CCV) for international transport could be used. More so, loading is not regular and could be contended in an event of climate disaster. However, the wellheads (7%) are ranked second to loading bays in terms of criticality. The wellheads are standalone systems as argued by one of the respondents who claimed that

"…wellheads are not easily impacted except by deliberate actions because they are controlled by regularly maintained pressure valves…"

Because it is almost a standalone infrastructure, they are placed on a highly fabricated cased surface with the capacity to withstand geothermal pressure from the well as well as external forcing from flood and storms. This makes wellhead adaptive and probably less vulnerable in the Niger Delta context and based on this study.

g. Proximity: as a criterion for vulnerability assessment in this study is an estimated distance between critical infrastructure and possible climate disaster zone. It is the measure of an infrastructure's distance to possible climate change impacts area. A vulnerability assessment by Denner et al (2015) of the Loughor Estuary shoreline (South Wales) revealed that infrastructures significantly vulnerable are those within short distances to the seashore.

The outcome of proximity in this study in *Figure 44*, suggests that pipelines (25%) and loading bays (20%) are the most vulnerable infrastructure in the Niger Delta. This implies that pipelines and loading bays are either located or run across various vulnerable terrains than other systems, hence the result. This outcome synchronises with the observational and face-to-face interviews where respondents concurred that

"…different sizes of pipelines…are connected to wellheads, flow stations and terminals and some…transport crude oil to as far as other West African countries…"

It was observed that pipelines across the region are subjected to constant flooding, corrosion, thermal expansion, thunder strikes, storms, and ocean tides, which could have reflected in the result obtained from this study. However, other systems are almost equally vulnerable (except for wellheads - 7%) and are directly related to their distance from the flood, tides, and storms zones. The result agrees with Denner et al (2015) and November (2004) who both argued that the further away an infrastructure is, the less vulnerable it could be to prevailing environmental risks in coastal areas.

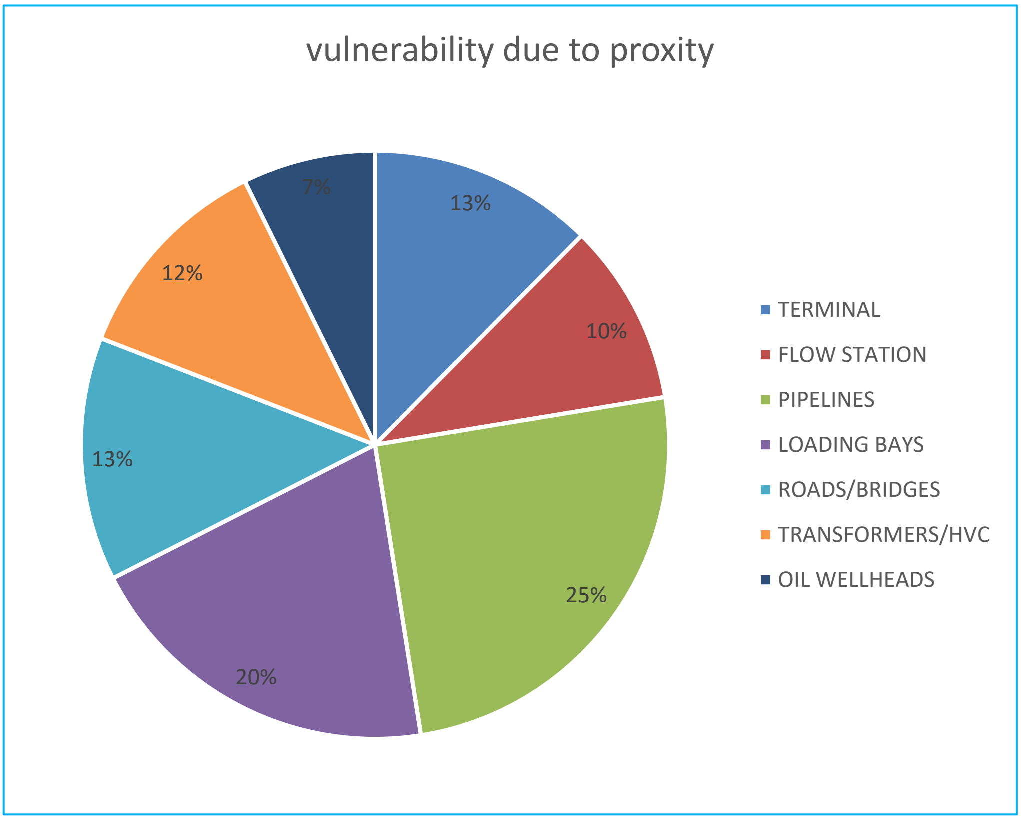

Figure 44 showing the vulnerability of critical infrastructure due to "proximity"

6.3.8 Consolidated vulnerability analysis:

This section presents consolidated vulnerabilities of all infrastructure according to the overall ranking outcome. The normalised principal eigenvalues aggregated in Table 13 are used to analyse the order of infrastructure vulnerability in this section. This section achieves the major aim of this study as it focuses on *the vulnerability of critical oil/gas infrastructure to climate change impacts*, presented in order of most to least vulnerable systems. The critical infrastructure with the highest percentage in ***Figure 45***5 below is said to be the most vulnerable to climate change impacts in the Niger Delta.

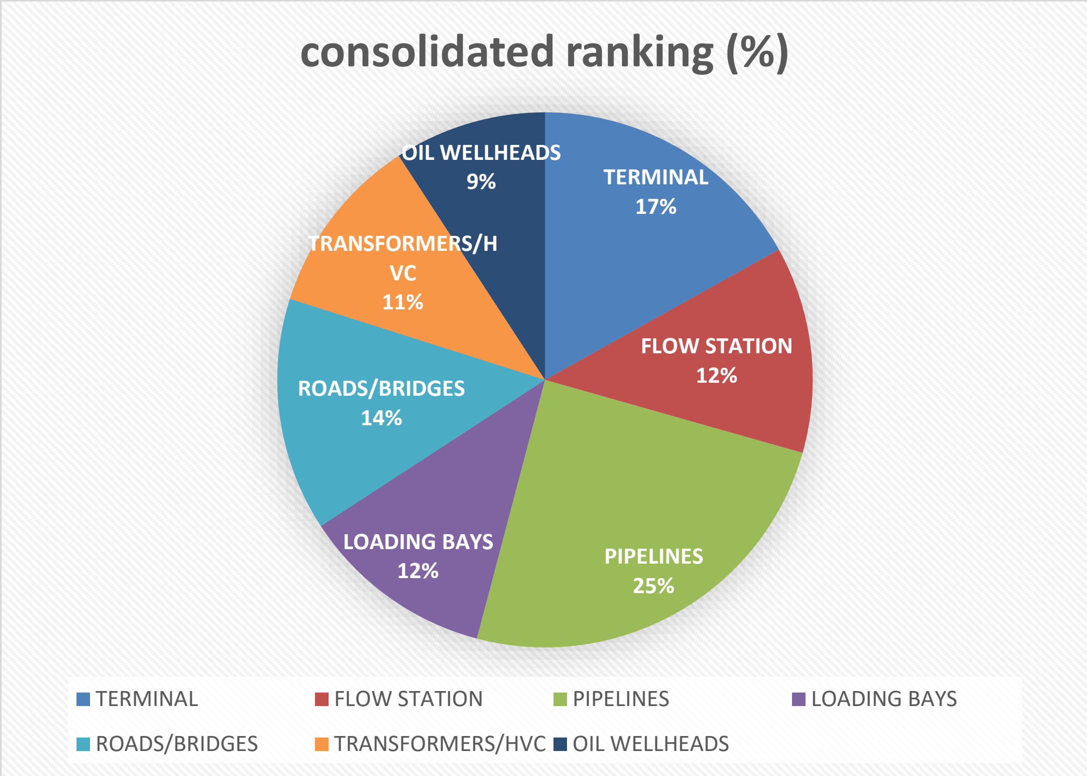

Figure 45 Consolidated result showing (in percentages) the vulnerability of critical infrastructure to climate change impacts in the Niger Delta

From Figure 455 above, consolidated vulnerability outcome indicates that pipelines are the most vulnerable assets to climate change risks in the Niger Delta with a vulnerability score of 25%. However, it was expected to be the least vulnerable critical infrastructure in this investigation because pipelines in the Niger Delta are constantly being replaced due to increasingly frequent attacks and vandalism (Obi, 2014; Ikelegbe, 2005; Anifowose et al., 2012). An investigation by Anifowose et al (2012) argued in support of the assumption that oil/gas industry in Nigeria has suffered its share of vandalism and substantial incidence of attacks and interdictions on oil and gas pipelines. This has led to regular replacements and rehabilitation of mostly pipeline systems. In a separate face-to-face interview with Assets Managers in the industry, they concurred that there are regular attacks on vital oil/gas installations in agreement with Anifowose (2012) but also contended that their *"…pipelines are not vulnerable to climate change because they are frequently being replaced after every attack…"* But field engineers agree contrary arguing unanimously that though pipelines are being attacked, there are some that have been "buried" (installed) for about fifty years and cannot be attacked but could still be vulnerable based on other factors. Other than age, some of these factors include exposure, the presence of burdens, proximity, interdependency, etc. because replacing a vandalised system in vulnerable location is insufficient to eliminate the vulnerability.

Judging from the "*Age of Infrastructure*" outcome in *Figure 39*, pipelines maintained a high vulnerability ranking with 27% score and implies that the vulnerability of pipelines depends more on other factors than on its age and obsolescence as contended. Moreover, "*Age of infrastructure*" contributes second to the least in criteria ranking for prioritising critical infrastructure in *Figure 35*, implying that it has less significance in the consolidated outcome.

Nevertheless, this investigation also revealed Terminals (17%) and Roads/Bridges (14%) as second and third most vulnerable critical infrastructure to climate change impacts in the Niger Delta oil/gas industry. Most oil/gas terminals in the Niger Delta are located on the inundated coast of the Atlantic with projected loading bays into the ocean for loading. Elevation statistics were scoped from Google map for five terminals in the Niger Delta and presented on

Table 14. Terminals are located on a range of 10 meters above sea level and could be judged as vulnerable due to proximity, exposure, and interconnectivity. Terminals in these locations face the threats and impacts of flood due to rising sea levels and Atlantic tides, frequent heavy rainfall and windstorms, which could potentially increase in the coming years.

Table 14 List of oil/gas terminals and their elevations in the Niger Delta

S/N	Terminal	Elevation (m above sea level)
1	Bonny NLNG	3 – 6
2	Brass	6 – 13
3	Quo Iboe	0 – 4
4	Forcados	4 - 13
5	Escravos	3 - 4.5

Roads/Bridges, on the other hand, could have ordinarily been considered as pedestal infrastructures in the industry but the exploratory stratification and opinions of stakeholders classified road transport systems as national assets that requires adaptation priority (Moteff and Parfomak, 2004b; Moteff and Parfomak, 2004b; Moteff, Copeland and Fischer, 2003). This study confirmed that transport assets such as bridges and roads are truly crucial and of both national and industrial priority. This result is in line with the submissions of Schweikert et al (2014) who advocated for a holistic maintenance system of road infrastructure for vulnerability to climate change as a means of sustainable economic delivery. More so, the Niger Delta geographical area is characterised by several 'bird foot' deltas that require bridges and access roads between islands and peninsulas for free movement of contractors, company staff, goods, and service around onshore platforms. This justifies its 3rd vulnerability ranking outcome and calls for corresponding adaptation strategies.

The result further revealed flow stations and loading bays as equally vulnerable obtaining 12% each and ranked 4th and 5th positions (Figure 45). Flow stations vulnerability result borders more on their criticality and sensitivity niche in the infrastructure value chain, age and proximity to climate risk. The loading bay, on the other hand, is up to 12% vulnerable due to adaptive capacity, exposure, and proximity indicators. Unlike the flow station, loading bays are interim transport infrastructure between the terminal and the transport ship. They are mostly exposed to flood, sea level rise and storms but often not sensitive as terminals or fragile as the flow stations. They are more resilient to coastal climate change impacts.

The least vulnerable critical infrastructures from this study are transformers/HVC and oil wellheads with 11% and 9% score occupying 6th and 7th positions in the vulnerability rank respectively. Transformers and high voltage cables convey electricity from the grid to platforms around the onshore facilities. Since the 2012 flood disaster in the Niger Delta, oil companies attempt to collaborate and proffered adaptation solutions for transformers by raising landing platforms by 5 meters above sea level. Initial electric concrete poles have been replaced with aluminium and metal poles systems for sustainable energy transmission. So far, this has proved sustainable and could have contributed to the least vulnerability outcome for transformers/HVC in this study. This outcome agrees with the existing argument that collaborative progress in adaptation planning is essential in reducing the vulnerability of systems in coastal areas (Rutherford, Hills and Le Tissier, 2016). However, the exploratory investigation revealed that metallic and cathodic materials are vulnerable to the combined impact of heat and saltwater intrusion that causes rust and corrosion. Nonetheless, the wellheads are critical infrastructure existing in isolated locations and connected only by delivery trunk lines to the flow station. Though the impact on wellheads could result in spill and damages to the ecosystems and human health, this investigation revealed that they are the least vulnerable to climate change impacts. Due to natural pressure, wellheads have controllable valves that regulate the flow of crude oil/gas from the wells, hence requires no electricity and assorted interdependencies, which often exacerbate climate impacts (Chappin and van der Lei, 2014).

6.3.9 Comparative cumulative analysis of criticality and vulnerability results

This subsection presents a snapshot comparison of result from a selected infrastructure based on their criticality and vulnerability ranking analysis. The aim is to further illuminate and test the relationships between vulnerability and criticality in each infrastructure by calculating the cumulative score from each segment. Details are shown in Table 15 below:

Table 15 Comparative analysis vulnerability and criticality outcome

Vulnerability Rank	Infrastructure	Vulnerability Score (%)	Criticality Score (%)	Criticality Rank	Cumulative score
1.	Pipelines	24.7	11.1	**5**	**35.8**
2	Terminals	16.9	27.1	**1**	**44.0**
3	Roads and Bridges	14.1	15.4	**3**	**29.5**
4	Flow Station	12.5	18.5	**2**	**31.0**
5	Loading Bay	11.7	8.6	**6**	**20.3**
6	Transformers/HVC	10.9	14.2	**4**	**25.1**
7	Wellheads	9.2	5.1	**7**	**14.3**

From the table above, pipelines are the most vulnerable and second least critical infrastructure while terminals occupy the reverse order. Furthermore, Terminals and Loading bays show similar "scissor positions" for vulnerability and criticality outcome - occupying immediate ranks above or below each other (2^{nd}/1^{st} and 5^{th}/6^{th} respectively) for both vulnerability and criticality outcome. However, the cumulative score indicates that terminals are the most outstanding infrastructure for both criticality and vulnerability indicators in the oil and gas industry. Cumulative score places the terminal as the most vulnerable critical infrastructure in the set while pipelines maintain the second most vulnerable critical. This implies that when planning adaptation strategies, pipelines are considered more vulnerable while terminals could be prioritised for the adaptation plans to cushion cascading impacts resulting from impacts on pipelines. As a justification, a respondent in the interview also portrays the terminal as the most sensitive and critical infrastructure in need of protection. He argued that *"…it is a 'no go' area in the industry because it is the heart of production, storage and transportation of products…"*

Furthermore, roads/bridges are the only infrastructure that shows consistency in both criticality and vulnerability assessment; occupying the third (3^{rd}) place in both assessment strata. It indicates that roads and bridges are as vulnerable as well as critical. Bridges and roads played a significant role during extreme events (Deshmukh and Hastak, 2010). Documentary data obtained from the exploratory survey also suggest that transport infrastructure if flooded could constitute serious risks, as it was the case in 2012. Roads/bridges provide major access to terminals and other critical onshore infrastructure including the transportation of crude.

Nonetheless, wellheads, like roads and bridges, consistently, occupy the last rank in both vulnerability and criticality assessment outcome with a cumulative score of 14.3%. This is because wellheads are less interdependent or linked to other systems (Wang, Hong and Chen, 2012b; Little, 2002). However, wellheads have in-situ electrical systems that power the functionality of oil uptake which its criticality and vulnerability is often overlooked. Wellheads are installed originally almost as standalone systems in vulnerable places with resistant capacities against flood, storms, rust, tides, and temperatures. The result implies that wellheads are though exposed but are part of the least vulnerable critical infrastructures. And this is the result is based on the criteria implemented in this study and due to less interdependency and tallies with the existing records (Chai et al., 2011). Cahi et al (2011) argued that interdependency between critical infrastructures could aggravate assets failure and possible vulnerability, hence further justifies the outcome of wellheads ranking in this study. Asset Managers and Planners in the industry could leverage this result for effective sustainable adaptation planning for other vulnerable systems in the Niger Delta.

6.4 DOCUMENTARY ANALYSIS

6.4.1 Introduction

Primary data for this study were collected in three forms according to the research strategy (section 4.3 Research Strategy) and framework (section 3.4.3 Vulnerability assessment). Quantitative data was collected through focus group interviews applying the AHP while qualitative data sets were collected from semi-structured interviews and documentary evidence. Exploratory observation yielded empirical graphics, maps, and publication evidence to establish documentary analysis and support qualitative and quantitative analysis. The aim was to incorporate triangulation in the study and address the limitations associated with qualitative and quantitative research designs (Bryman, 2016). Sections one and two analyse the criticality and vulnerability of infrastructure from AHP standpoint. Both criticality and vulnerability analysis used a set of different multicriteria in synthesising the decision-making process. Extracts of the face-to-face interview were considered in both sections of the chapter to further strengthen and corroborate results.

This section analyses the documentary evidence (hydrological maps, charts, and graphics) related to the vulnerability and impact of extreme climate cases (such as flood) on critical oil/gas assets in the Niger Delta. Documentary data formed part of the evidence of flood impacts on critical oil/gas infrastructure in the Niger Delta between the year 2000 and 2016. Unlike sections one and two, this section presents an advance descriptive analysis to further illuminate evidence of the vulnerability of the study area to present future impacts of climate change on oil/gas infrastructure. Data from face-to-face interviews are jointly analysed to strengthen the result. The analysis is based on specific factors that could exacerbate climate impacts such as hydrology, basin system, water discharge rate, and evidence of vulnerability (the 2012 case study).

6.4.2 Vulnerability due to the Hydrological structure

Data on the hydrological system showing annual flood predictions and probable flood-prone areas were obtained from the publications of the Nigeria Hydrological Services Agency (NIHSA) available from oil company's databases. The agency was established in 2010 with the responsibility of monitoring and reporting hydrological vulnerabilities after monumental losses associated with growing flood incidences across the country. NIHSA (2016) argued that recent extreme weather events are impacting on lives, *damaging critical infrastructure*, disrupting socio-economic activities and fundamentally, displacing communities and settlements within flood-prone areas. This claim agrees with academic theories on the impact of the flood as reckoned by Tanaka et al (2017) and Mahmood et al (2017). However, the key responsibilities of NIHSA are to advise the public, and decision makers across private and public sectors (such as the oil/gas sector) on "operational hydrology, water resources activities and to issue a forecast on flood, drought, and other extreme weather events" (NIHSA, 2016).

NIHSA further argued that they apply scientific and multi-agency collaboration techniques to engage with relevant agencies such as Nigeria Meteorological Agency (NiMET) and National Emergency Management Agency (NEMA) for efficient data gathering and tactfulness in publishing annual flood outlook (AFO). The AFO creates public awareness and enlightens relevant stakeholders including the oil and gas industry and the academia on probable flood risk areas. In the context of oil/gas infrastructure vulnerability in the Niger Delta, publishing annual flood outlook is not substantial to deal with the bigger picture and scale of the problem. A follow-up approach through community enlightenment and awareness campaign is crucial because the operations of oil/gas activities in the region depend largely on how the communities and other relevant stakeholders are involved; as part of companies' corporate social responsibility (CSR) (Idemudia, 2012). The investigation revealed that emergencies and all plans for flood and other extreme weather prevention must effectively incorporate the social community in the planning for sustainable adaptation and continued successful operations in the context of oil/gas industry (Ijaiya, 2014; Idemudia, 2014).

NIHSA installed hydrogeological and hydro-meteorological monitoring stations in specific locations along the Niger and Benue rivers to acquire essential statistics. Though the parameters for selecting locations is not mentioned in NIHSA (2016) annual flood outlook, it is contended that telemetry data collection platform (DCPs), groundwater monitoring wells (GMW) and automatic weather observation stations (AWOS) were used. These data are used to model "*probable"* flood scenarios and seasonal rainfall predictions (SRP). Probable flood scenarios data from monitoring stations are analysed by geospatial stream flow model (GeoSFM), and soil and water assessment tool (SWAT) to produce flood maps (***Figure 47***).

The effectiveness and urgency of the data gathering process due to the frequent devastating flood events across Nigeria in recent times has triggered a cross-sectoral concern for relevant agencies and stakeholders. These extreme weather events such as rising sea level, heavy downpour, storms, and flooding have severe implications for the coastal areas where critical infrastructure sustainability is compromised.

To present evidence of vulnerability from geospatial stream flow model probable flood risks maps, a control map of Nigeria (***Figure 46***) showing normal River Niger and Benue (blue lines) is placed below free of flood and other extreme events. However, GeoSFM model maps are used in presenting detail analysis to underpin areas of vulnerability.

Figure 46 Map of Nigeria showing Niger and Benue rivers

In ***Figure 47***, blue patches show probable floodplains as pathways to flood vulnerability. It also indicates that areas along the rivers Niger and Benue were more vulnerable to flooding in 2015, including some parts of the Niger Delta.

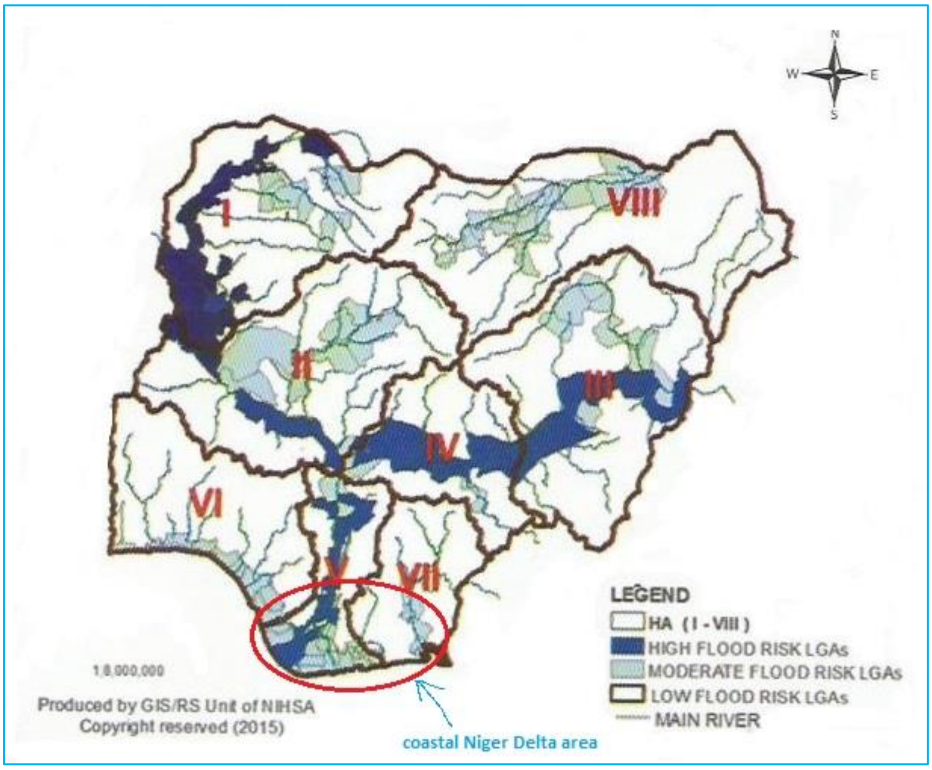

Figure 47; Map of Nigeria showing the 2015 national probable flood risk (vulnerable) areas with a focus on the coastal Niger Delta. Source; NIHSA (2016)

Flood-prone regions are classified based on impact magnitude as; high, moderate, and low risk in local government areas (LGAs) represented by blue-grey and white patches. Flood prediction was estimated to cover a specific distance from the river; up to 1 km for high flood areas while up to 2 km and 3 km respectively for moderate and low floodable areas (NIHSA, 2016). This implies that infrastructure located 1, 2 and up to 3 km away from the Rivers Niger/Benue troughs in the Niger Delta are either highly, moderately, or least vulnerable to flood events. From ***Figure 47***, high flood risk areas align in the '*Y*' shape corresponding to the river Niger and Benue troughs (see ***Figure 46***). This implies that the major rivers are sources of vulnerability to flooding and presents clearer evidence of critical infrastructure exposure to flood by proximity to the Niger/Benue rivers. Based on this map, probable flood risk area in the Niger Delta coast (circled red) in 2015 was narrow and skewed South-West in the coastal zone. This implies that there was a narrow severity extension of about 1 km in addition to the flooded area and an expanded 'moderate flood risk' areas. The existence of an expanded 2 km moderately floodable area is an indication that a slight increase in the amount of rainfall or river over overtopping could trigger high and severe flood in subsequent years. Kuswanto, Andari and Permatasari (2015) argued that climate change extreme events are occurring faster than scientific predictions and could exacerbate more impact on vulnerable areas (including critical infrastructure) in subsequent years. This implies that assets located in ‘moderate flood risk’ areas on the map in 2015 could be at high flood risk in subsequent years. This indicates an increase in vulnerability and justifies the inclusion of *proximity* as one of the multiple attributes (criteria) for vulnerability assessment in this study.

Nevertheless, documentary data on 2016 AFO could confirm this analysis to buttress the arguments of expanding vulnerability in this study. Hydrological models for the year 2016 show a significant difference observed in the thickness and expansion of probable flood risk areas; with even more noticeable expansion along River Niger down to the Niger Delta (see *Figure 48*). The Niger Delta states - Akwa-Ibom, Bayelsa, Calabar in Cross River, Delta, and Rivers; and most sub-basins across Nigeria upscaled from being moderate flood risks areas to high flood risk. It indicates the increasing vulnerability of critical infrastructures along the Niger Basin and plain. As suggested by the changes in the hydrological models, severe flood incidences were reported in most of the probable areas across the country in 2016 and 2017. *Figure 48* shows that ‘high flood risk” areas exist more along the river Benue route, upper river Niger and the coastal Niger Delta. This is because of most inland rivers within the Middle-belt (II, IV, V and some part of III), South-South (VII and part of V), North-West (I) and most parts of the North-East (part of III) on the map; empty into the Niger/Benue river troughs. The encroachment of high flood risk areas is aggravated by increasing frequent heavy downpours across Nigeria (Israel, 2017). This implies that rainfall is directly related to the magnitude of flood events discounting the dam and river overtopping effects at the upper Benue Rivers in Cameroon.

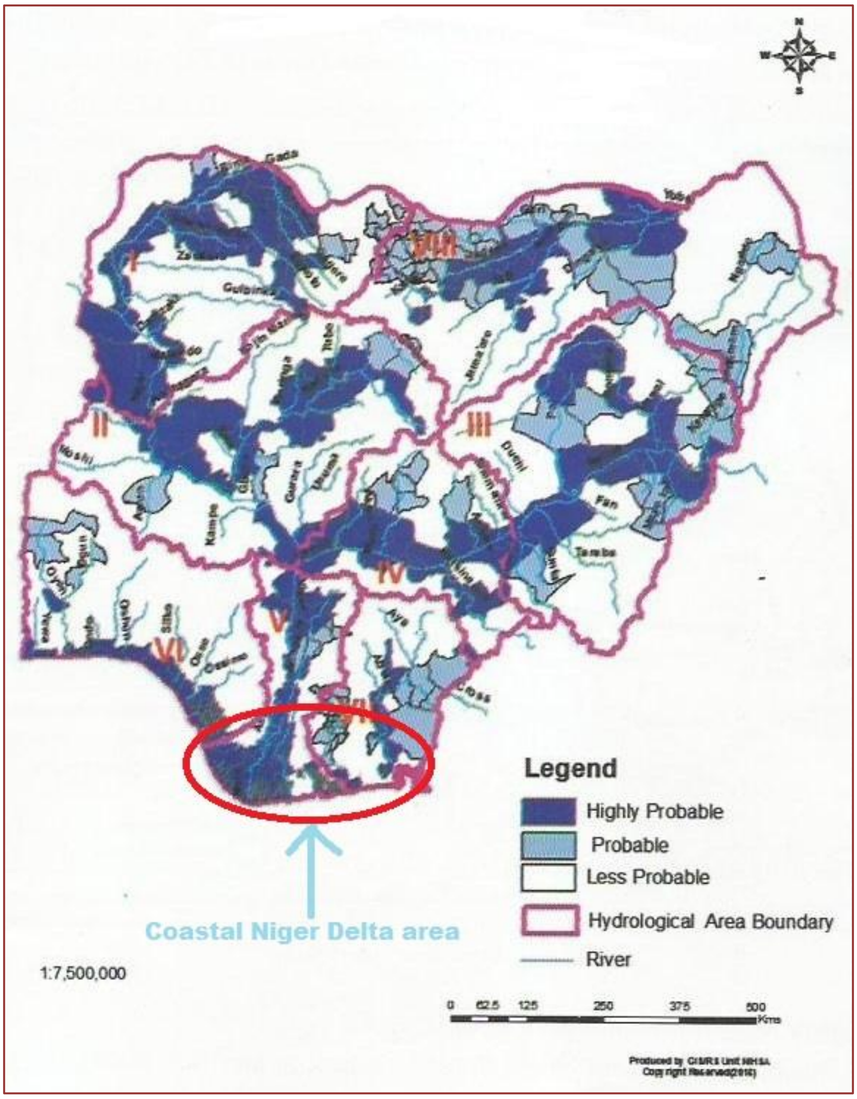

Figure 48 map showing probable flood risk LGAs for the year 2016. Source: NIHSA (2016)

It was suggested that climate change could force regular extreme events such as flood resulting from heavy downpour and sea level rise with severe effect on infrastructure (Adejuwon, 2012; Nzeadibe et al., 2011). The implication for the oil/gas industry is a complete exposure and disruption of assets and operational activities in vulnerable platforms located in the Niger Delta. This evidence justifies the rationale for a pragmatic vulnerability assessment embarked upon in this study; with the view of suggesting sustainable, resilient and resistant adaptation alternatives for oil/gas assets.

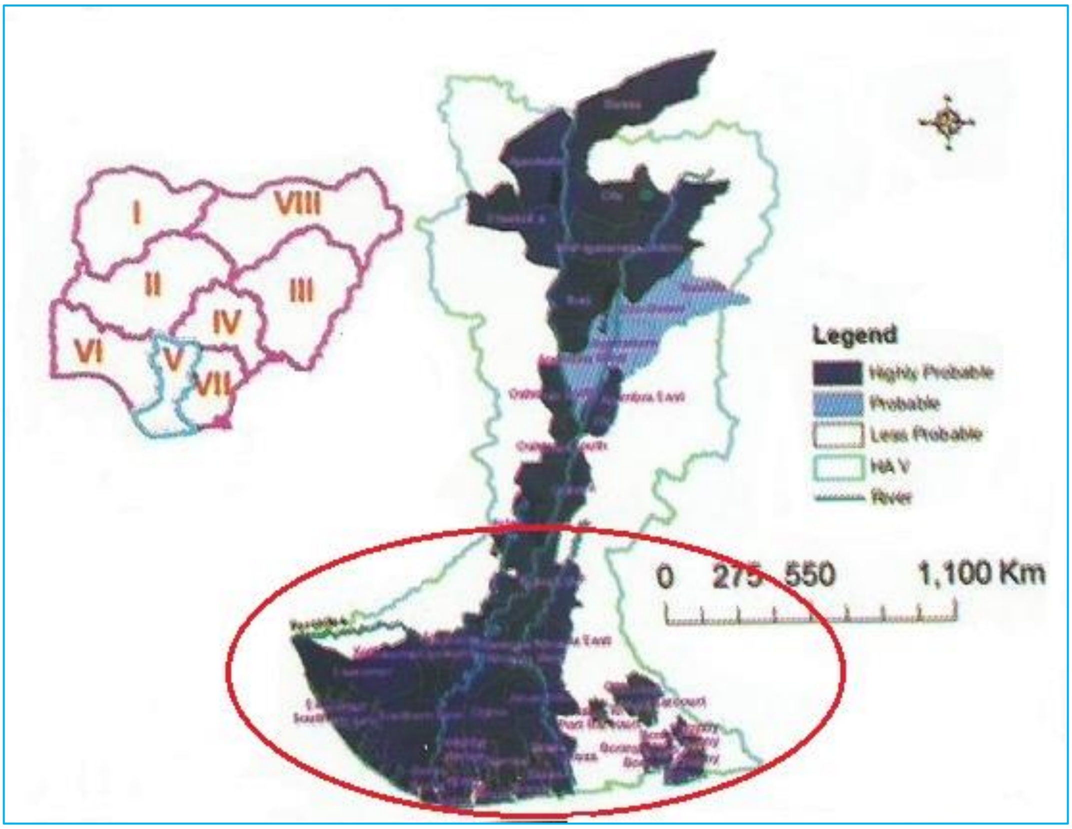

Figure 49; showing expanded highly probable flood risk areas along the river Niger trough and the coastal Niger Delta. Source: NIHSA (2016)

Figure 49 present clearer and extended flood risk areas of the River Niger trough and the Niger Delta. The circled area indicates the core coastal area and expanded high probable flood risk area in 2016. A critical comparison of *Figure 49* and ***Figure 47*** shows a significant difference in terms of an increase in the size of the high floodable area beyond 2 km as earlier predicted. This justifies the earlier assumption that subsequent geospatial stream flow models may show an increase in vulnerability due to rapid rise temperature, frequent and heavy rainfall, windstorms, etc. arising from climate change. The map also indicates that areas initially estimated as moderately vulnerable (about 2 km from the river basin) in 2015 have been significantly submerged by highly probable flood risk in 2016. This evidence agrees with the postulation that future changes in climatic conditions could exponentially defile scientific predictions (Hinkel et al., 2014). This expansion of flood risk areas and continual changes in the climate system raised critical questions on the sustainable operations of critical onshore oil/gas infrastructures located in this region. Hence, responsible organisations and sectors require a pragmatic approach of sustainable adaptation planning, implementation and continual review. This is offered by the framework designed in this study

Furthermore, from observational assessment revealed that anthropogenic issues exacerbate the impact of the flood through blockage of inundated drainages and hydrological troughs, interference with Natural River courses through Agricultural practices and unplanned constructions. NIHSA further argued that the presentation of early warnings and sensitisation of relevant stakeholders in the past three (3) years has *"…reduced/prevented flood impacts in some predicted areas."* But evidence from field observations and interviews in this study revealed that flood incidences in the region are not being prevented by awareness creation. This is because NHISA lacks the regulatory capacity to build adaption mechanisms, hence may have only succeeded in reducing the social impacts such as providing temporal settlements for flood refugees. Therefore, the vulnerability of all systems in geographically vulnerable areas persist and behoves on assets owners in different sectors (such as the oil/gas) to embark on adaptation investment towards preventing the impact of the flood.

However, to effectively advance more on adaptation alternatives for shortlisted infrastructure in this study, an insight into the hydrological changes that occur in the Niger Delta basin is particularly analysed. This in-depth analysis could further illuminate the vulnerability and criticality of infrastructure to climate change and lead to possible adaptation suggestions.

6.4.3 Vulnerability due to the basin structure

The Niger basin is the largest drainage system in West Africa covering an estimated area of about 2,170,500 km^2 (*Figure 50*) a colossal landmass about twice the size of Nigeria and thrice the size of France, bigger than any five West African countries. It implies that about this size of land is likely to be flooded in case of river overtopping from prolonging rainfall in the coming years. However, with the concerted global effort in climate mitigation to reduce global warming, flood events may be reduced. Previous analysis indicates that extreme flood events due to changing climate in the West African sub-region have led to sudden weathering and tearing of built infrastructure. Figure 50 shows the widening drainages and vulnerable floodplains along the River Niger from Fouta Djallon highlands in the central Guinea Republic. It stretches through Mali, northern fringes of Burkina Faso, southern Algeria, Niger Republic, parts of Benin Republic and northern Cameroon, occupying a substantial part of Nigeria.

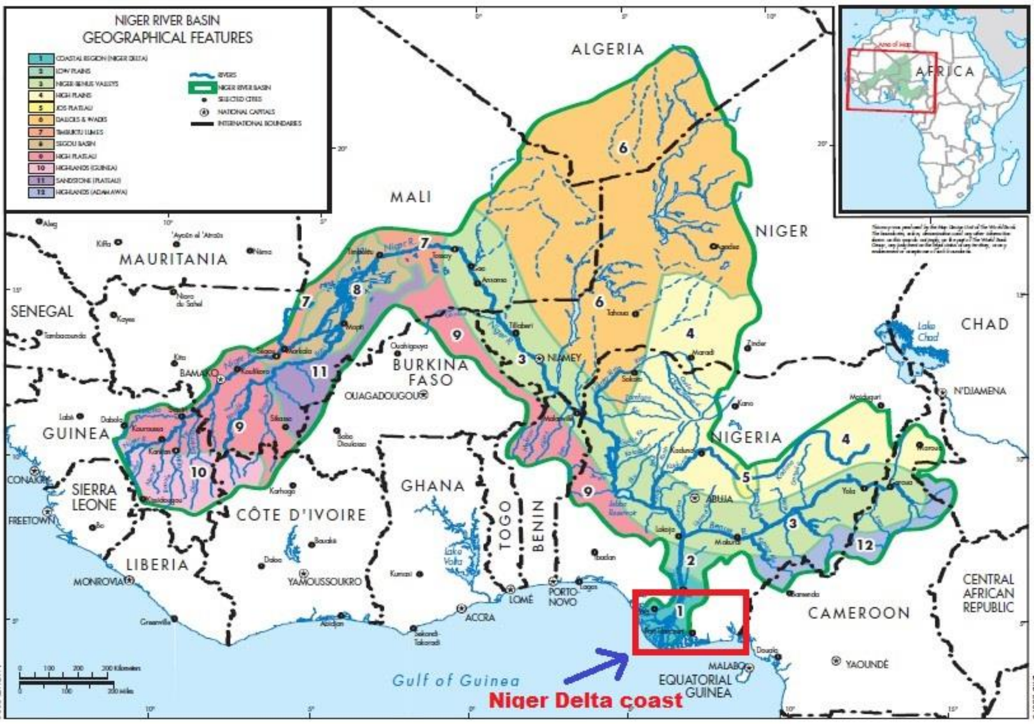

Figure 50; showing the network of the Niger drainage system and indicated Niger Delta. Source: Total E&P Nigeria, 2016

The Niger drainage system has become a concern for most West African countries especially Nigeria where about 70% of the total land area lies in the drainage core. *Figure 50* confirms the vulnerability predictions recorded in NIHSA (2016) hydrological flood maps shown in *Figure 47*, *Figure 58*, and Figure 49 respectively. It further presents the extent of vulnerability of the Niger Delta (the squared red area on the map). It indicated that half of the Niger Delta lies in the vulnerable Niger drainage basin and could be submerged in an event of a flood. This is because the entire Niger drainages empty into the major River Niger which discharges into the Atlantic around the Niger Delta coast. Unfortunately, water discharge into the Atlantic from the River Niger is opposed by strong waves of the Atlantic Ocean; pushing back into the continental shelves, gradually submerging shorelines and causing inland water overtopping. The meeting point between the discharged water, the surging tides and a corresponding rise in groundwater; pose a severe threat to the Niger Delta coast and widen the vulnerability gap. Implications of these threat indicators occurring simultaneously could leave the Niger Delta and inherent critical oil/gas infrastructure submerged in the coming decades if climate conditions continue to aggravate (Lai, Yang and Chen, 2017).

6.4.4 Vulnerability base on water discharge rate indicator

Water discharge rate is the measurement of runoff speed or flow rate along rivers, canals, drainage effluents, streams, or simulated channels in industrial settings. The reason for measuring water discharge rate and synthesis of turbines efficiency, budgeting and water accounting including control of flow systems and regulation and flood monitoring (Pant et al., 2016a). Procedures and processes of water discharge rate modelling are outside the scope of this study, but hydrographic data analysis could illuminate the vulnerability of the Niger Delta. It also shows how WDR could affect critical systems and cause a climate-induced flood at different intervals of hydrological timescale (*Figure 51*). This analysis attempts to justify the argument that water discharge rate is directly related to the probability of flood occurrence in the Niger Delta scenario (Toonen, 2015; El Bastawesy and Abu El Ella, 2017) and implies that high water discharge rate signals potential flood incidence. Available data on water discharge rate, taken at the confluence of rivers Niger and Benue, could be used by decision makers in the oil/gas industry in planning sustainable adaptation for upstream and downstream sectors of the industry.

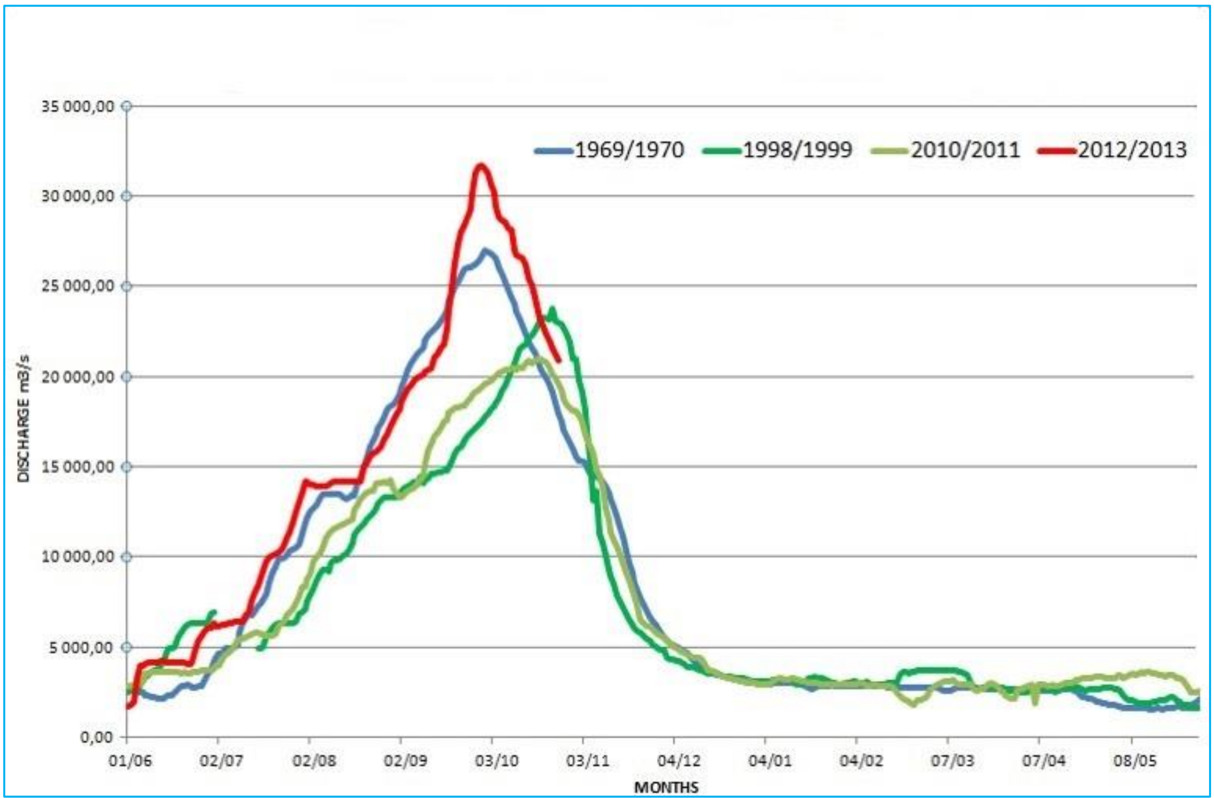

Figure 51; showing comparative flood hydrographs of River Niger monitored in Lokoja, Nigeria. Source: NIHSA (2016)

Hydrographs above shows the discharge rate of river Niger after its confluence with the Benue River in Lokoja town. From interviews, the choice of measuring discharge rate at Lokoja is informed by *"…the need to consider the combined discharge rate effect of water volumes and runoff from the two rivers to enable us plan for flood in the coast"*. Knowledge of combined water discharge rate is used as a monitoring mechanism for determining possibilities of the flood at the lower Niger Delta coast. It presents decision makers and engineers with accurate data to decide which possible adaptation plans to trigger at different intervals of flood occurrence as argued by Zhao et al (2017b).

NIHSA (2016) hydrographs show water discharge rates taken at four (4) timescales; 1969/70, 1998/99, 2010/11 and 2012/13 between the months of June and May. The result was used to monitor the behavioural relationship between water runoff (speed) along the Niger River and flood incidence in the delta coast (the case of 2012). The blue hydro-gradient (1969 and 1970) indicate that there was a rise in water discharge rate with a peak of 27,000 m^3/s between September and October of 1969 and decreases steadily in subsequent years. In 1998 and 2000, the discharge rate peaked at 24,000 m^3/s and 21,000 m^3/s respectively with a shift in peak months from September/October to October/November, each with some noticeable flood and river overtopping. This shift is attributable to changes that occur in the natural geochemical and water distribution cycle (Beniston and Jungo, 2002). The overall reduction in water discharge rates could also be attributable to the construction of ***Lagdo dam*** at the upper Benue River in the Republic of Cameroon between 1977 and 1982. It is argued that Lagdo dam holds a high volume of water from the river basin thereby reducing the discharge rate and flooding capacity (Haile, Tefera and Rientjes, 2016). It is further contended that a significant quantity of water has been diverted from the Niger basin into *Kainji* and *Jebba* dams and from Kaduna distributary into *Shiroro* dam for other economic purposes. Diversion of water could have caused the reduction in water volume and discharge rate as shown in *Figure 51* but with the rising rate and amount of rainfall, rivers might regain water above their initial capacity, hence increasing the likelihood of flood.

Nevertheless, the 2012 flood tragedy in the oil/gas industry is reflected in the models presented in the red hydrograph. This evidence justifies the claim that the water discharge rate is directly linked with flood occurrence in the Niger trough. The red hydro-gradient path shows a sudden increase in water discharge rate from about 21,000 m^3/s to about 32,000 m^3/s in the month of October 2012/2013 data year. Before the recent cases of flood, there has been a once in decades flood that possibly submerged communities and damaged some structures. Tami and Moses (2015) concurred that there have been cases of flood in Nigeria within the past four decades, but the incident of 2012 took the entire nation by surprise with severe consequences on biodiversity, social and built infrastructure and sustainability. They argued that about 500,000 barrels of crude oil output were lost. They contended that post-disaster need assessment (conducted between November 2012 and March 2013) with the support of the World Bank, UN, and Global Facility for Disaster Reduction and Recovery estimated the cost of infrastructure damage at USD $9.6bn. Tami and Moses (2015); Aloysius (2012); OLOGUNORISA (2004) corroborates this argument with the records of NIHSA (2016) that extensive low lying heavy industrialised coastal areas (853 km) are vulnerable to flood impacts which could have severe cost in repairs, adaptation and recovery process.

The steep rising limb of 2012/13 hydrograph indicates the sudden rise in WDR and the occurrence of the flood. It represents a corresponding rise in the rate of flood beyond the 1969/70 and 1998/99 records from June to the end of August and stagnated at 14,000 m^3/s up to mid-August. Discharge rate increases steadily from mid-august to mid-September and suddenly increased rapidly (parallel slope to the 'y' axis) through the rest of September (*Figure 51*). Participant in the face-to-face interviews confirmed

"…that water discharge rates peaked on 29th September 2012 with a record discharge rate of 31,692 m^3/s and flood level at 12.84 m; the highest in records of flood since I started working in the oil and gas industry".

The hydrograph also shows that peak periods for water discharge rates are often short and declined rapidly as indicated by the falling limbs. However, the rapid and steep falling limb is unrelated to flood water recede rate down Niger Delta. This is because, Permatasari, Natakusumah and Sabar (2017) posit that there are other geomorphological factors that determine the flow rate of an uncontainable flood watershed. Some of these include the *permeability of the soil and accessibility* of river channels that allow the seepage of water on a normal river base flow, basin control system, relief, and basin size. In the river Niger drainage system, most of its upper and mid topographies are a mix of hills and floodplains allowing water flow into restricted locations. The bed foot delta could have provided easy access for water discharge into the Atlantic Ocean, but the relatively flat relief and narrow sizes of distributaries and closeness of groundwater aggravated the flood. More so, frequent heavy downpour exacerbated the vulnerability of the coast and inherent critical oil/gas infrastructure to flood as concurred in the study by Willems et al (2012) and Mahmood et al (2017).

6.4.5 Evidence and consequences of vulnerability (the 2012 flood)

As discussed in the sub-sections above, the 2012 flood incidence presents very severe consequences on critical oil/gas infrastructures. The severity of flood impact occurred because of the failure of oil and gas companies to respond to significant changes in water discharge rate and the absence of knowledge on the expanding flood risk on Niger hydrological structure. The level of impact also depends on the porosity due to basin drainage structure and absence of adaptation mechanisms. The corresponding effect significantly impacted on oil mining lease (OML 58) operated by Total Exploration and Production Nigeria (TEPN) (Figure 522). OML 58 lies in the heart of Niger River floodplains (*Figure 49*) between Orashi and Sombriero rivers which were overtopped by the high volume of water discharged. The severity of impact on the platform confirmed the vulnerability indicators (presence of burdens, exposure and proximity) designed for analytic hierarchy process assessment. It further corroborates the opinion of NIHSA (2016) that some vulnerabilities are due to anthropogenic construct and blockage of existing watershed or floodplain. This implies that heavy downpour at the upper ends of either river Niger or Benue could catalyse cascading flood events with severe impact in the delta coast. Therefore, continuous monitoring of water activities along the Niger River trough and sustainable adaptation culture is crucial.

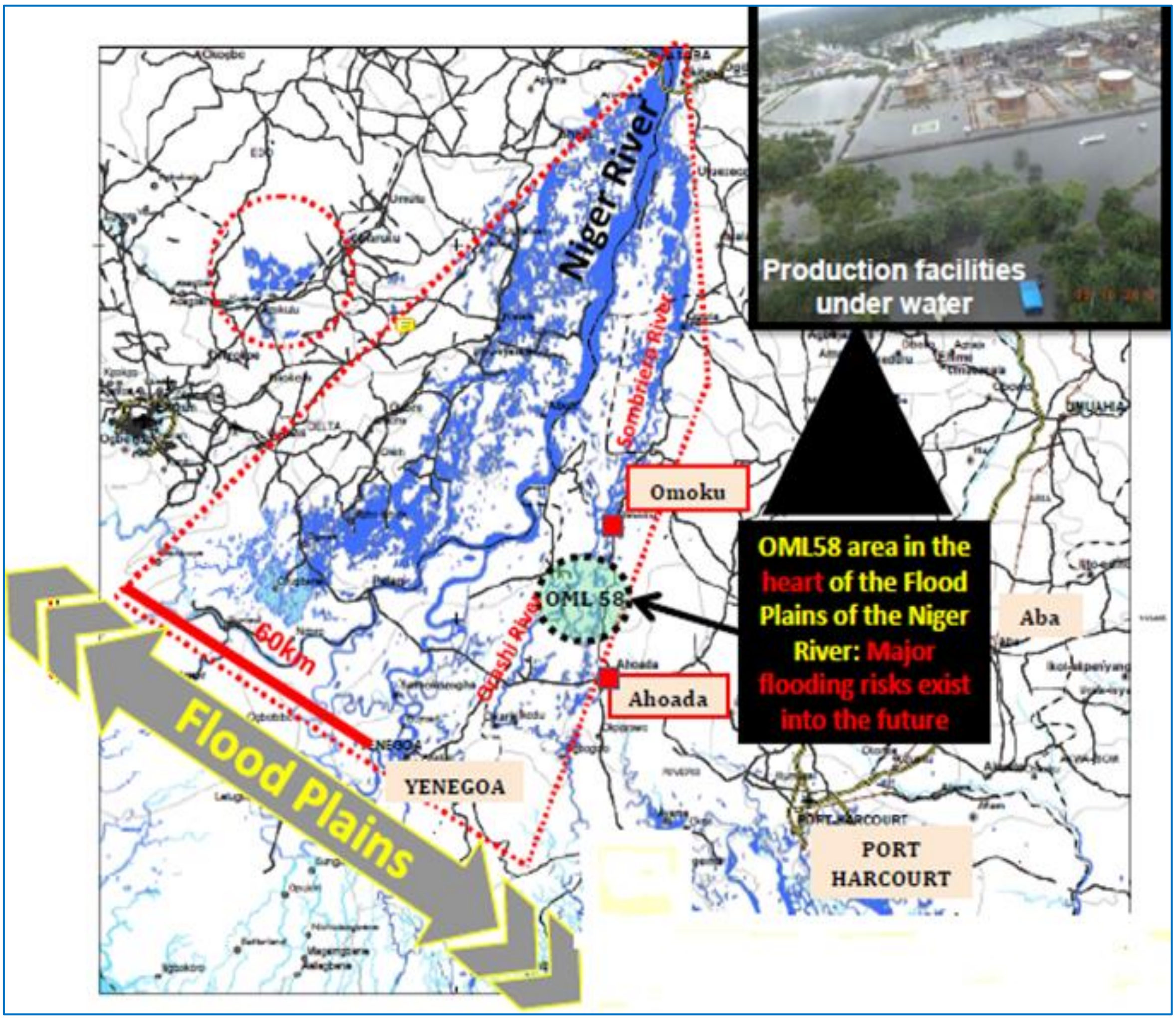

Figure 52; showing OML58 being submerged by 2012 flood water in the Bayelsa state, Niger Delta. Source: Total E&P, Nigeria

Figure 54 below shows the OML 58 on a normal climate system. The platform is an onshore JVC of TEPN and NNPC with the shareholding capacity of 40% and 60% respectively. It has in it storage tanks fed by a network of trunk lines running from various wellheads and pipelines, access roads, internet servers and telecom, transformers, HVC for electricity supply, manifolds, etc. Also, interconnected infrastructure in the OML 58 is the Obite and Ogbogu flow stations. The cascading impacts on interconnected systems as evidenced justifies the inclusion of "*interdependence*" as a criterion for AHP analysis in this study.

Interviews revealed that in 2008, an assets upgrade was launched to improve OML 58 installations and oil recovery processes by 2011 but the flood-devastated these improvements and other ambitious projects (see *Figure 54* and *Figure 55*). This is an indication that systems upgrade and installations in the Nigerian oil and gas industry have not commenced the inclusion of climate impact assessment in assets management and guidance in the oil and gas industry regulations. This study aimed to suggest this process for infrastructure and environmental protection in the region.

Figure 53; showing OML58 Obagi GRA flood capacity on 12th October 2012

Figure 54; showing OML58 Obagi GRA flood capacity on 12th October 2012

The intensity of the flood impact could have halted system upgrade probably because contractors failed to infer the possibility of flood and vulnerability of the OML 58; implying that most stakeholders are still ignorant of flood and its impacts between September and October in the Niger Delta. The flood incidence was also blamed on the Lagdo dam overflow in Cameroon though it is contended that the Management extended warning information on preparedness to the Nigerian Foreign Affairs department. Interview respondent argued that *"…the flood warning issued from Cameron was not extended to us, so we had no knowledge of flood possibility at the time"*. All these led to the impact shown in *Figure 55* and 56 below.

Figure 55; showing OML58 Obagi GRA after the flood on 9th of November 2012

Figure 56; Western and Southern views of the flooded OML 58 in 2012

6.4.6 Probable causes and Impacts of OML 58 Flood

This study uncovers vulnerability as the primary cause of the 2012 flood impact on OML 58 onshore oil/gas platform in Bayelsa state. The investigation revealed that the entire platform and its host Obagi and Ogbogu communities were submerged by floodwaters from the 297 km long Orashi and 197 km long Sombriero Rivers. These are distributaries of the main Niger River (*Figure 522).* The face-to-face interview data revealed that the river Niger floodplain is a highly probable flood area of

"…*about 15 km west of the platform site with connections to other minor floodplains…"* This indicates that distributary river overtopping (at a distant over 15 km) along a floodplain poses significant threats to sensitive assets and social life in the region. This implies that the major Niger River can spill through floodplains and adjacent low lands and river distributaries and submerge isolated land strips and oil mining field (OMLs) up to the distance of 15 km.

Nevertheless, the flood intruded into the general restricted area (GRA) majorly due to its location along a floodplain or proximity to overtopped Niger River which exposed the entire system to very severe impacts. It was gathered from interviews that floodwater emerged from the north wing of the OML 58 and OFS and built high pressure on parameter fence. The black arrows in the figure below show the direction of water flow and areas of collapsed GRA fencing.

Figure 57b; showing schematics of flood direction and a collapsed wall in the OML 58 and OFS. Source: TE&PN (2013)

In the platform, the volume of water continued to build up pressure enough that submerged storage tanks, flow station, emergency diesel generators and transformers (EDG & T), etc. As expected, the build-up pressure collapsed parts of the southern GRA wall, creating emergency flood speedway through the integrated operational site, exacerbating more washing effects on the entire sensitive system. Interviews further revealed that the severity of the flood was blamed on the release of water from the flooded Lagdo dam, the capacity of which was exceeded by the excessive rainfall in the upper Benue River (Republic of Cameroon). Accordingly, the interviewee argued that

"The Cameroonian government was alleged to have communicated flood warning signal across to their Nigerian counterpart urging a prompt preparedness, but such memos were not transmitted to us…"

Further consultation with other participants across the selected respondents confirmed that Cameroonian flood warning signal was not further transmitted to relevant stakeholders in the flood impact management value chain. It implies that there is a third factor of vulnerability - *poor communication management* and the relationship between concerned stakeholders. Hence, by the 12th and 13th October of 2012, water discharge rate rose rapidly with a corresponding increase in its volume in the Niger River drainage system. The resulting flood at the lower Niger spilt excessively across floodplains into the oil/gas platforms causing TE&PN and other corporations to declare a force majeure (emergency shutdown) operation in OML 58 and other marginal fields. TE&PN accompanied the force majeure with a red security alert for OML field operations and for the commencement of safe evacuation of personnel on as well as the entire Obite community dwellers. Declaration of force majeure and raising alert systems across the industry confirms that there is a gap in specific adaptation structure in place. (see section 5.4).

Nonetheless, several levels of impacts were recorded in lowly built OML 58 marginal field ranging from loss of site accommodation and structures, loss of access roads and bridges, disruption of external power supply cables and communication networks causing de-energisation and depressurisation of plants. Other impacts include power cut that stranded the Obagi and Ogbogu community dwellers. The incidence posed an overwhelming complicated scenario for emergency responders in the industry who according to interviews have never been confronted with an extreme flood event. Interviews with management officials revealed that *"…the emergency shutdown of OML 58 cost TE&PN about 104 kboep/d and some unaccounted non-operated JV with SPDC…"* at the period of global peak oil price. Interview respondent claimed that *"…about 500,000 bbls of oil was lost in all marginal field operations* [the entire Niger Delta] *causing a drastic reduction in export…"* and agrees with the records of Tami and Moses (2015). As expected, some of the losses were because of the considerable spill from tanks, forming oil sheen pollutant spreading across to residential areas, surface water pollution and distortion of biodiversity.

6.4.7 More Evidence of 2012 flood impact on critical oil/gas infrastructure

The 2012 flood raised very serious concerns across boards in various locations in the Niger Delta. This study presents the oil industry case citing the OML 58 platform because of its portents visible vulnerability indicators and relates with attributes applied in ranking vulnerable systems in sections one and two of this analysis. The flood impacted all phases of oil/gas assets operations including the environment, social and economic lives of host communities. ***Figure 62*** obtained from exploratory field investigations indicates that a significant amount of oil spill occurred - leaving deposits of emulsifying free phase crude oil entangled in wood debris. An oil spill has severe short and long-term implications with potential linkages to impact on infrastructure development, communities and ecosystems across the world as could be applicable in the Niger Delta context (Ifelebuegu et al., 2017; Singleton et al., 2016; Grattan et al., 2011). Climate change could potentially exacerbate some of these impacts and further complicate under listed issues in the Niger Delta;

a. Damage of ecosystems: both onshore and offshore spill spread on marshland, beaches, rock surfaces, sand and form shin slick on surface water systems. Oil slick damages mangrove forest, shrubs, fibrous plants and disrupt food chains in the ecosystems leading to the death of plants and animals.
b. Spill oil contaminates surface and groundwater destroying domestic and commercial water use as well as reducing the photosynthetic ability of light-dependent aquatic organisms. Spilt oil spread, disperse, fragment, and forms sediments in the river or sea beds constituting a potential threat to fish, sea mammals and endangered species.
c. Loss of economic activities occurs when the environment is contaminated as an indigenous population who depend on the forest and rivers for survival get stranded. In the Niger Delta, the oil spill has a history of community and oil company crisis which if not properly handled, climate-induced environmental issues may trigger fresh crises.
d. Company reputation; oil spill and environmental abuse has caused severe reputation damage and the lingering crisis between Ogoni people and SPDC (Boele, Fabig and Wheeler, 2001; C. I. Obi, 2000). This and other pockets of oil-related crises in the region have heightened awareness and community anger in the region that should prevent further spill by any circumstances.
e. Litigations and fine; all over the world, consequences of the oil spill are usually accompanied by controversial legal suits. Lessons are learnt from the Deepwater Horizon case in the Gulf of Mexico blowout which cost BP $61.6 billion USD (Brooks, 2003). Though legal processes in the Nigeria case stand a chance of being compromised, lawsuits delay business operations, constitute extra cost, and damages the international reputation of international oil companies (IOCs). Legal actions may not consider accidental claims of unplanned extreme events such as flooding, hence, multinational, and local oil companies have the responsibility of preventing an oil spill in all circumstances.
f. Impact on assets; the 2012 flood submerged roads, bridges, electrical and telecommunication equipment in various operational platforms in the Niger Delta. Severe damages to these systems imply extra cost that affected companies and increase in insurance premium.

Sustainable adaptation strategies in place could eliminate or reduce this cost and maintain a continued operation that ensures customer and investor's confidence and trust in the supply chain.

Though legal operations and framework may differ between countries, litigation in the Nigeria oil and gas industry are strongly benchmarked by other African crude oil economies such as Ghana, Liberia, Angola, etc. Spill-related legal issues in the Niger Delta has dented corporate images of most IOCs across Africa (Willis and Weiler, 2013). Therefore, pragmatic adaptation is required in the Niger Delta to ensure that such is replicated across the continent.

However, flood-related spills could complicate environmental management and clean up practices for the organisations and regulatory bodies such as the Department of Petroleum Resources. Flood water transport oil slick across hundreds of miles, contaminating surface fresh water, arable land, and ecological components. Oil and Gas companies require a pragmatic and effective flood adaptation response mechanisms and reinforcement of all critical and sensitive assets in the Niger Delta to deal with flood impacts. This is crucial because it is suggested that the continued expansion of "high flood risks" areas and the possibility of high water discharge from the upper Niger and Benue rivers is imminent (NIHSA 2016).

Figure 57; Spilled crude oil trapped with receding floodwater

Figure 58; Trapped oil forming emulsification sheen after floodwater recedes

Figure 59; showing spilt oil film being contained with booms. Source: TE&PN (2012)

Figure 60; Trapped crude oil on debris being recovered during clean-up process after flood

Figure 61; Flooded EDG and transformers at the OFS. Source: TE&PN (2012)

Figure 62; flooded separators at the OFS. Source: TE&PN (2012)

6.5 *Emerging Cases*

This section presents the emerging cases of adaptive capacity and vulnerability of critical infrastructure to climate change impacts arising from an exploratory investigation in this study. The first case describes the Chevron elevated platform, which abated the impact of 2012 flood and ensures continues operations while marginal fields located in low elevation were shut down. Case II presents an empirical impact of rising temperature on flow stations underpinning how an increase in ambient temperature could disrupt the functionality of sensitive infrastructure. The aim of presenting these findings is to justify the eminence of climate risks *(presence of burdens*) and vulnerability of the Niger Delta and justify the need for sustainable adaptation in the oil and gas industry.

6.5.1 CASE 1; Chevron Platform

The Chevron platform is an isolated case that resisted the impact of 2012 flood. The investigation revealed that it is a marginal filed operating about 6 km to the north of OML 58. The circled flame indicates that while OML 58 was shut down due to emergency flooding, Chevron continued operation amidst the same disaster.

Figure 63; showing Flooded OML 58 and Operational Chevron platform during the 2012 flood in the Niger Delta. Source: TE&PN (2012)

Interview in this study revealed that *"Chevron continued operation was possible because the field is relatively new, and it's built on an elevated platform above the flood water level."* It implies that elevating platforms for infrastructure above expected flood water level could reduce the level of impacts or at least to the barest minimum and support continued operation. Continued operation in the marginal field amidst flood disaster confirmed the possibility and effectiveness of platform elevation as an adaptation strategy. This case also indicates that some companies could be aware of flood impacts through confrontational measures by default, some operational sites are sited on elevated locations.

6.5.2 CASE II Impact of Temperature and the Compressors

Climate change scenarios indicate that global temperature is rising with a cascading increase in regional ambient temperatures. This implies that an increase in global temperature result is the mean increase in temperature in different regions and zones of the world and vice versa. Sensitive infrastructures such as those operated by thermodynamic systems, are easily influenced by the increase or decrease in ambient temperature. Flow stations are some of the thermodynamic operated systems in the oil and gas industry due to the separators, which require a cyclic flow of cool water around separators to reduce the temperature of crude oil during the first phase of separation. Though the minimum temperature required for operation of flow station in the Niger Delta was not supplied, it was gathered that in recent times, some level of disruption has emerged in the functionality of the compressors.

In this special case, interviews revealed that the flow station was disrupted mostly at mid-day when the sun peaks and the temperature rise higher than normal. This apparently caused an average increase in the ambient temperature around the separators, hence slow down the optimal operations of the system. It was revealed that the contracting company carried out a complete overhaul of the systems and the result shows that the mechanisms were at optimal design function without wear or tear. This result raised concerns in the company as production was affected. An experiment was designed in December 2016 to detect the cause of flow station underperformance by logging production output and temperature. Separation rates were logged against time of the day and temperature for five days. It was observed that separators were at consistent optimal performance between 22:00 and 11:00 hours and highly disrupted between 12:00 and about 21:00 hours. However, while it is established that increases in ambient temperature were instrumental to system disruption, the exact values at which temperature peak was not given.

Nonetheless, this case as expressed by assets managers demonstrates that rising global mean temperature could pose a significant impact on sensitive and thermodynamic infrastructure both in the oil and gas and other industries. This implies that assets managers and designers are expected to adapt to the projected temperature to ensure sustainable resilience of sensitive systems up to the year 2100 when the temperature could peak at 2°C.

6.6 Chapter Summary

This chapter presented the result and analysis of the criticality and vulnerability of climate change impacts on oil and gas infrastructures in the context of the Niger Delta. The analysis is in line with the major aim of the study and contains three subsections. Each section focuses on a distinct element of analysis – AHP criticality and vulnerability while documentary analysis is performed to strengthen and triangulate the study. Section one focuses on how quantitative analytic hierarchy process (AHP) was implemented in the analysis of the criticality of selected oil and gas infrastructure from a multi-stakeholder decision-making approach. Specific criticality criteria applied in prioritising assets for criticality includes *replacement cost, societal relevance, impact on the ecosystem, impact on human health and safety, availability of an alternative, the effectiveness of the alternative and interdependence*. It is found that the criticality of infrastructures in hierarchical order are; terminals, flow stations, roads/bridges, transformers/HVC, pipelines and oil well heads and loading bays.

Section two also applied a quantitative AHP in evaluating the vulnerability of arising critical infrastructures to climate change impacts. The following criteria were applied; *exposure, interdependence, proximity, the presence of burdens, criticality, adaptive capacity and age of infrastructure*. It is found that vulnerability critical infrastructure in hierarchical order is; pipelines, terminals, roads/bridges, flow stations, loading bays, transformers/HVC and wellheads.

The analysis in section one and two demonstrate how multiple choices are pairwise compared according to specific criteria in an oil and gas industry through multi-stakeholder participation from an academic standpoint to produce a hierarchical database of criteria, critical and vulnerable oil and gas infrastructure, in the case of the Niger Delta.

Section three focuses on the qualitative analysis of documentary evidence collected from an exploratory survey of the study area. It extensively illuminates the concept of vulnerability in the context of the Niger Delta and portrays the criticality of selected oil and gas infrastructure. It analyses vulnerability due to the hydrology and basin structure of the Niger trough, water discharge rate as an indicator of the possibility of the flood at the lower Niger, evidence, and consequences of vulnerability. More evidence of vulnerability is analysed based on the impact of the 2012 flood, the case of OML 58. Analysis revealed that flood could be directly linked to water discharge rate as indicated in the hydrographs from NIHSA geospatial stream flow model (GeoSFM). It could, therefore, be deduced that monitoring water discharge rate and perhaps groundwater monitoring is a crucial flood adaptation strategy in the Niger Delta case.

The chapter also presented two emerging issues (cases) that were not in the initial research plan but are of high significance in vulnerability and adaptation studies. The emergence of these cases further justifies the applicability of framework which is open to accommodate emerging systems in vulnerability assessment. Case one (I) describes and analyses the Chevron platform which elevation enables it to adapt to flooding and ensured continual operation at the peak 2012 incident in the Niger Delta. The analysis showed that critical infrastructure stalled on high platforms above sea level could adaptation to flooding in line with other studies of coastal areas (Denner et al., 2015; Balica, Wright and van der Meulen, 2012; Rosenzweig et al., 2011). Case II briefly analyses the observation of the impact of rising temperature on the separator system of a flow station in the Niger Delta. It showed that as global mean temperature increases, there is a corresponding increase of local ambient temperature that could disrupt the mechanical efficiency of thermodynamic sensitive infrastructure such as flow stations. Therefore, the need for expedient action on adaptation planning and investment is crucial in the Niger Delta oil and gas industry. The next chapter addresses detailed salient issues on adaptation strategies suggested for the oil and gas industry in the context of Niger Delta.

CHAPTER SEVEN

SUGGESTED ADAPTATION STRATEGIES

7.1 INTRODUCTION

The major aim of this chapter is *"to suggest sustainable adaptation strategies for vulnerable critical oil and gas infrastructures in the Niger Delta…"* which address the second aim and fifth objective of the study. It also addresses the question; "*What possible alternative adaptation strategies can be adopted for the protection of critical oil and gas infrastructure in the research area?"* Suggested adaptation strategies are selected based on the prevailing climatic challenges and flood occurrences in the Niger Delta. Some of these options are assessed and analysed according to expert's viewpoints arising from interviews and review of relevant literature sources from IPCC and most referenced sources on climate adaptation technologies on coastal disaster management and practices. From the study framework, these measures are expected to be mainstreamed to improve the resilience and resistance of critical vulnerable infrastructures. Vulnerable infrastructures are prioritised through the application of analytic hierarchy process (AHP) in the previous chapter and include Pipelines, Terminals, Flow stations, Loading bays, Roads/Bridges, Transformers/HVC and Wellheads. Though the adaptation strategies are analysed, they are only suggested with the expectation that each strategy could be further decomposed to underpin the technical, scientific, economic and environmental implications of adopting any given options. Accordingly, a detailed investigation is required to conduct cost and benefits, technical merits and interdependencies involved in the fabrication and installation of any option(s). It is also imperative to note that the suggested options in this study are not exhaustive and certain as other measures could evolve as technology and research continue to advance with the uncertainties associated with climate change (Gersonius et al., 2013). The chapter reviewed the purpose and analysis of adaptation and presents three (3) main adaptation constructs for the oil and gas industry. These include physical design and building of adaptation structures, strategic institutional responses and Emergency response mechanisms.

7.2 Review of Adaptation purpose

The purpose of adaptation of critical infrastructure is to build processes of resilience or resistant adjustments of critical assets coupled with organisational assets management strategies that aid infrastructure to cope with climate stressors (Rutherford, Hills and Le Tissier, 2016; Mostegl et al., 2017). Though it is unclear from existing literature on the niche of assets management as a critical approach to adaptation, the investigation revealed that the discussion on adaptation from a strategic standpoint is crucial in sustaining infrastructures. Varianou et al (2017b; Jude et al (2017) argued that adaptation to climate change embraces the construct of both physical and effective strategic planning which lies in the managerial ability of a given industry. In this case, policy formulation, legislative adjustments and design of suitable adaptation frameworks are central to critical assets resilience and resistance building. The purpose of adaptation, therefore, is to ensure that critical infrastructures have the required physical resilience, resistance and managerial concern through policy design and legislative lobby to withstand climate risks, in the Niger Delta.

7.2.1 Resilient adaptation

Resilient adaptation involves pragmatic plans that protect existing or planned vulnerable infrastructures from the impacts of extreme climate disasters such as storm surge, flood, or rising Atlantic tides; and their mechanical integrity is maintained without any permanent damage. Resilience adaptation in the Niger Delta context implies that when operational disruption eventually occurs, operations should resume rapidly within a short period of time (Pursiainen, 2017; Chang, 2014).

7.2.1 Resistant adaptation

Resistance, on the other hand, involves planning adaptation structures that make critical infrastructures self-proof and excluded from impacts of extreme climate events such that normal operations continue steadily during the period of impacts (Burton, 2016).

It is further contended that effective adaptation comprises of four main processes of data gathering/literature review, suggesting and planning, designing/implementation and evaluation/monitoring (Klein, Nicholls and Mimura, 1999). This segmentation hatches a new challenge in the process as it becomes more complex, time consuming and commitment of resources which may deter vulnerable industries from timely actions. However, in this study, data gathering was concluded through interviews and review of literature for data gathering in the Niger Delta. The second phase which centred on suggesting and planning is the focus of this chapter which seeks to highlight appropriate actions for the oil/gas industry in the Niger Delta case. The designing/implementation and monitoring/evaluation of performance are outside the scope of this study, but the framework provides a pointer (mainstreaming) which assets managers could adopt to complete the adaptation value chain.

7.3 *Spatial Adaptation planning in the Niger Delta oil/gas industry*

To fully understand the suitable adaptation strategies for critical infrastructure resilience and resistance in addition to those highlighted in previous chapters, a brief review of how some indicators could influence spatial adaptation alternatives in this study is crucial. This review ensures that suggested adaptation alternatives capture the spatial elements of the environment (ecosystems and community ambient) which are synergistically vulnerable (Tami and Moses, 2015). To this effect, this chapter, therefore, follows the suggestion of Sano et al (2015) who argued that "external and internal dimensions of vulnerability" could inform an integrated adaptation framework. In the context of the Niger Delta, it captures spatial environmental elements and focuses on critical indicators such as adaptive capacity, exposure and sensitivity. Because oil and gas infrastructures in the Niger Delta are highly inter-linked, Mikellidou et al (2017b) emphasise that synergistic impacts assessment is required. To effectively incorporate spatial systems in the assessment, infrastructures in the region could be integrated according to mini-segments giving rise to networks-of-network clusters. Implementation of the research framework in this study could typically scope the infrastructures available in the industry sectors - upstream, midstream, and downstream sectors. Spatial adaptation planning in the Niger Delta context incorporates all systems including urban centre, ground and surface water and ecosystems relevant to oil and gas activities in the region. It is an intra and inter-dependency adaptation-based approach (Chappin and van der Lei, 2014). Spatial adaptation planning, therefore, encompasses intra and interdependencies as well as the ambient environmental factors such as ecosystems and residential communities as in the case of the Niger Delta.

The rationale for this spatial planning stemmed from the contention that climate change impacts have the potential of cascading disruptions due to synergistic effects on vulnerable adjacent and unprotected systems which are weak, sensitivity and exposure. Conventionally, cascading impacts spontaneously flow from point of origin to receptor destinations but Amin (2002) argued that in sensitive sectors such as energy, there is a possibility of impacts in either side of origin and receptor network streams. This could rapidly cascade broadly in adjacent directions impacting interconnected systems with the potential of spilling over. Hence, identifying various interconnectivity of infrastructure value chain in the context of the oil and gas industry is central to adaptation planning.

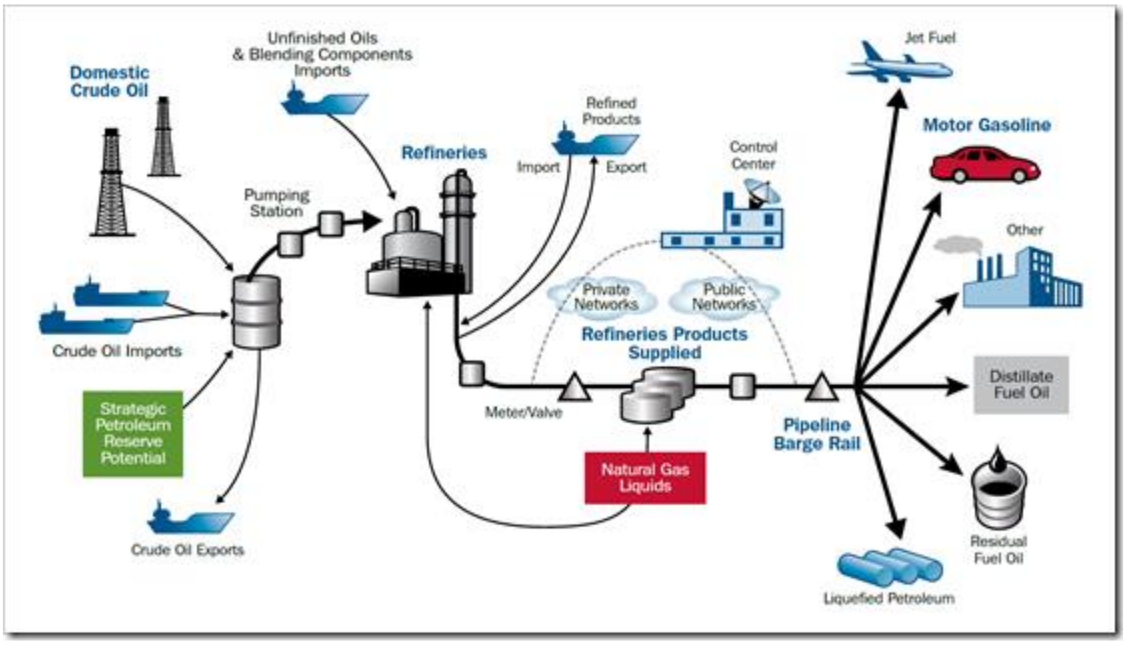

Figure 64; Level of Interconnectivity and Dependencies in the oil and gas industry. Source: (Dixon, 2010)

7.4 Climate Adaptation Response in the oil/gas industry

Critical infrastructure protection is contended to be a relatively new domain of scientific exploration. Initially, critical infrastructure protection and adaptation response considered a generic focus on energy, transport and telecommunication assets from terror attacks in the US (Karabacak, Ozkan Yildirim and Baykal, 2016). With the emergence of climate change impacts (sea level rise, increasing temperature and storm surges), this study has extended adaptation response through research to a more specific area in the oil and gas industries with the Niger Delta as a case study. This study will provoke the concept of adaptation planning, investment and response strategies, fully integrated into the oil/gas environmental management policy. In a review of critical infrastructure vulnerability to climate change conducted by Mikellidou et al (2017b) in the EU, 82 papers published between 2001 and 2017 were reviewed to underpin the success of critical infrastructure protection in the energy industry. Only 3.6% were focused on the oil/gas industry with none of them fulfilling the indicators set out to benchmark a holistic assessment (impact, interconnections, and adaptation resilience). More so, researchers contended that attempt to suggest adaptation for the oil and gas industry could be uncertain because of so many interrelated variables in climate forecasting (Longwell, 2002). In this study, it is argued that technology has evolved, scientific predictions have incrementally become more accurate and consistent in terms of climate-related forecast making adaptation planning and response more reliable, credible and crucial.

In view of evolving technologies and frequency of extreme weather catastrophes, stakeholders in the oil/gas industries have commenced high-level discussion of infrastructure protection through adaptation investment. In practice, this discussion is still very limited in the Niger Delta oil/gas industry. Essentially, strategic adaptation highlights the development of frameworks for effective oil/gas coastal management through effective protection and restoration (Sano et al., 2015; Phillips, 2015). Other strategies include the development and integration of adaptation policies into existing legislation and effective collaboration with the government and the private sector for climate change adaptation. However, while crude oil remains the global leading energy demand, accounting for 32.9% of global energy consumption indicating a steady trajectory up to 2050 (British Petroleum, 2017), the industry in the Niger Delta showed less attention to physical climate change adaptation research construct. There are less investment and structured planning mechanism for systems resilience which exacerbates vulnerability. In this study, it is argued that adaptation for critical oil/gas infrastructure includes construction of dunes and flood defences, shoreline erosion control systems, hydrodynamics monitoring. Other are sediments transport evaluation, beach nourishment and improved operational platform designs; in anticipation of flood arising from sea level rise and agrees with Sano et al (2015).

Operating in vulnerable coasts such as the inundated Niger delta could adopt efficient resources management with the aim of making oil/gas infrastructure resilient and sustainable for long-term purposes. In this system, community participation is an integral aspect of the resources management framework to ensure that customary operations are in line with resources exploration and conservation. Community participation is essential in the Niger Delta context and could involve the cooperation of associations such voluntary organisations, women and youth groups, local government, Universities, and community leaders (Idemudia, 2014; Lunn, 2003).

Another segment of adaptation response is the appraisal and development of critical infrastructure standards for vulnerable coastal areas such as the Niger Delta. Sano et al (2015) reviewed adaptation strategies in coastal areas from an Australian standpoint and argued that the National and Territorial Governments could facilitate adaptation framing through policy direction and setting of standards. These policies include encouraging and incentivising communities to invest in renewable infrastructure while protecting standard fossil energy systems. Also, key in the adaptation process for energy assets which could be relevant in the Niger Delta case is; tacit and explicit knowledge sharing and exchange of ideas between government agencies, the private sector and communities (Azhoni and Goyal, 2018; Riege, 2005). It is further contended participatory systems management approaches and sharing lessons learnt from best practices between organisations in an integrated network of professionals, experts and policymakers have become a prominent strategy in shaping local adaptation response (Burton, 2016).

However, not all strategies could be relevant in the Niger Delta context. To achieve objective five (5) of this study, highlights of sources of vulnerability in the Niger, critical infrastructure at risk, and suggested adaptation mechanisms that are appropriate practices for the industry are considered.

7.5 Sources of Vulnerability threats in the Niger Delta

From this study, sources of infrastructure vulnerability in the Niger Delta include:

i. Frequent heavy rainfall, leading to reoccurring flood events
ii. Increasing temperature
iii. Saltwater intrusion increasing corrosion of metallic infrastructure
iv. Heavy and regular storms surge associated with lightning discharge – interfering with electrical and telecommunication signals in various platforms
v. Widespread inundation – prime receptor indicator of river overtopping and oceanic surges

7.6 Analysis of Vulnerability threats

Climate burdens in the Niger Delta pose significant threats to the prioritised critical infrastructure and the general built environment including the spatial systems in the region. These threats can be responded to through two fundamental approaches; **mitigation** (top-down) and **adaptation** (bottom-up) approaches argued by Füssel (2007). However, this study focusses on the bottom-up adaption element as a means of protecting vulnerable critical oil/gas infrastructure from the impact of flood, rust etc. because of the urgency and intensity of climate threats - occurring rapidly. From interviews, a respondent argued that;

"…flood is now recognised as a potential risk factor for our [oil and gas] operations. It has never been like this for over 60 years. It is a new dimension of risk in the industry, so personnel are retrained, and we are learning from experience to tackle the issue; it happened without our knowledge and we responded well with the benefit of anxiety in 2012…as the entire Niger Delta that was flooded…"

This statement suggests that the threat of flood is becoming frequent and tackling the problem only occurs as the event unfolds. The statement confirmed that there are no concrete and well-thought adaptation strategies in place if they are "…*learning from experience…"* This further confirms the position of Jude et al (2017) and Jiricka et al (2016) that there is a gap in infrastructure protection in the oil and gas industry. Hence, adaptation inclusion in this study is strategic, timely and valuable for the oil and gas industry, especially in the Niger Delta vulnerability context.

7.7 Analysis and Justification of Adaptation Inclusion in this Study

To justify the inclusion of adaptation in this study, a brief comparative analysis of the characteristics of adaptation and mitigation are highlighted. This is because some experts could use mitigation and adaptation interchangeably and that could potentially affect the credibility and justification of adaptation planning in the industry. Mitigation as a top-down climate solution approach is argued to have been overemphasised by the Intergovernmental Panel on Climate Change (IPCC), National, and Regional governments. Its focus is on emission reduction targets. Despite this huge investment, impacts of prevailing global warming effects on critical infrastructure have continued to intensify (Jiricka et al., 2016; Mikellidou et al., 2017b). Whereas the IPCC technical adaptation guideline and response strategy to sea level rise, for instance, failed to accommodate specific and compelling guidelines on protecting critical systems, oil and gas industry is compelled to adapt with pragmatic steps. This is because mitigation is a long-term strategy for a future solution to global climate change, unlike adaptation, which could be provided in a short-term to specific areas of vulnerability such as the coastal Niger Delta. The differences between mitigation and adaptation and some justifications for adaptation in this study are presented in

Table **16** below:

Table 16; justification of adaptation in the study

Mitigation	**Adaptation**	**Justification of the study**
Aimed at reducing greenhouse gases emission and impacts of warming at a global scale	Localised and specifically to systems, usually of high national interest in specific industries and locations	This study focusses on specific critical oil/gas infrastructure in the Niger Delta and seeks to suggest industry-specific adaptation alternatives
Benefits are certain because it is aimed at addressing the root cause of climate issues from global perspective	Benefits and effectiveness of adaptation depends on regional climate data often affected by uncertainty	Data analysed in this study are obtained from the Niger Delta. The uncertainty of climate issues means adaptation can be localised with elements of flexibility
Concerned with global Pollution that leads to global warming	Concerned with specific areas of extensive vulnerability such as coastal lowlands	The Niger Delta is located along the Atlantic coast with significant evidence vulnerability, hence adaptation need
Greenhouse gases emissions reduction is a global priority for long-term mitigation	Adaptation strategies are short term, complex, and rest on niched vulnerable organisations	This study identifies a vulnerability in a niche industry with the responsibility of addressing own complex vulnerabilities

Furthermore, the adaptation concept in this study is crucial because of cumulative anthropogenic effects of gas flaring in the Niger Delta. This is being contended to have extensively exacerbated global warming with severe impacts on the regional climate systems (Hegerl et al., 2007). It is projected that by the mid-21st century, mean water runoff would increase by 10 - 40% in the tropics and the most vulnerable locations are coastal areas and floodplains such as the Niger Delta (IPCC, 2014). The report adds that developing African countries are the most vulnerable challenged with multiple stresses of climate impacts arising from flood and storm surges. It is further argued that the global climate could change faster than forecasts due to the existing harm already caused by emissions (Bondyrev, Davitashvili and Singh, 2015). This is evident in the past seven years, which has continued to show an increase in global temperature in succession; each year is warmer than the previous (Wang, Jiang and Lang, 2017). More so, emission reduction effects are argued to take decades to become noticeable, implying that the impact of warming could persist for several decades to come. In view of this, the inclusion of adaptation (resilience and resistant) strategies in this study for the sustainability of vulnerable critical oil and gas infrastructure in preparedness for the worst-case scenarios in the Niger Delta currently is an appropriate and credible argument. Though mitigation appears to gain much popularity and attention in the debate of climate change than adaptation, failure to adapt could pose severe threats to critical infrastructure in the Niger Delta and other aspects of developing countries (Füssel, 2007).

7.8 Analysis of Adaptation need arising from this Study

This study found that increasing cases of flooding, high precipitation, and land loss due to rising Atlantic tidal levels in inundated landscapes of the Niger Delta have severe impacts on critical infrastructure. The vulnerability of High Voltage Electric transmission cables, Transformers and Emergency Diesel Generators (EDGs), Pipelines, Terminals, Flow stations, Roads/Bridges, Wellheads and Loading bays; at different hierarchies to extreme events is consequential for the industry in the region. As stated earlier, the consequences are beyond the industry as more than 75% of Nigerian Government revenue comes from crude oil trading. This implies that without effective and efficient adaptation measures in place, investors and the national government stand a chance of suffering significant losses. It is further argued that while scholarly activities on climate change in the oil/gas industry focus on Environmental and Social impacts and analysis, adaptation strategies are often not captured. More so, Policies and Government Regulations focus on Environmental Impact Assessment with significant discrimination for assessment on how climate threats could impact on critical infrastructure (Wilby and Dessai, 2010). In addition to Economic reliance on oil revenue, lack of scholarly and policy direction for adaptation, climate threats have continued to prevail in the Niger Delta. From these examples, it is deduced that there is an urgent need for adaptation investment and institutionalisation of the concept of adaptation in the Oil and Gas sector. The urgency of the problem and the sensitivity of the Niger Delta situation to the global economy also necessitate the need for proactive adaptation/adjustments in the operations and study of sustainable infrastructure vulnerability value chain.

Adaptation investment and timely planning allow experts and practitioners to prepare for emergencies and minimise potential cost implications of climate impacts (Aguiar et al., 2018; Kazmierczak and Carter, 2010; Kuklicke and Demeritt, 2016). Effective and sustainable adaptation strategies provide the essential resilience required to effectively maximise the economic benefits available from the Nigerian oil/gas industry. These strategies are significant components of climate disaster response, which could minimise impacts while being complemented by concerted mitigation effort aimed at sustainable reduction of GHG emissions for the long-term (Smith et al., 2009; Jorgenson, 2006; Santer et al., 2003).

In agreement with the positions of Kröger (2008), Huang, Liou and Chuang (2014), Theoharidou, Kotzanikolaou and Gritzalis (2010a), Chappin and van der Lei (2014), this study found that impacts of extreme weather on critical infrastructures have the potential of cascading to other linked and dependent systems. The exploratory survey revealed that frequent heavy rainfall, flood, and storm surge often constrained the use of social amenities such as potable water, shelter, and access to medical facilities in host communities. This poses a potential threat of possible outbreak and spread of diseases and pastes, extension and spread of spilt crude, power outages, etc. To avoid these cascading effects, there is a need for adaptation planning for critical infrastructure protection and limitation of linkages.

7.9 Analysis and Presentation of Adaptation Strategies

This section analyses and present selected adaptation strategies in the Niger Delta context. Climate change adaptations are context specific and vary according to the region of implementation and depend largely on the scale of prevailing impacts or impacts in the forecast (Aguiar et al., 2018; Radhakrishnan et al., 2018). It implies that while adaptation planning is a crucial way forward, a critical analysis underpinning the context of implementation is also emphasised in the industry. In this study, adaptation concepts are presented in three subthemes; a) structural adaptations b) strategic adaption and c). Emergency response adaptation. Stakeholder viewpoints and analysis of subtheme is presented to further underscore the strengths, preparedness and acceptability of adaptation opportunities available to the oil/gas industry in the Niger Delta.

7.9.1 Structural Adaptation and Analysis

Structural adaptation measures are tangible and innovative technologies implemented by relevant organisations to prevent or reduce the impact of climate risks on critical infrastructure. In the Niger Delta case, the flood is the dominant climate risk impacting infrastructures (Tami and Moses, 2015). Other forms of physical adaptation measures include construction of elevated platforms for safe operation, construction of flood defences, buffer zones, and proper channelization of water and substitution of vulnerable systems with innovative, resistant and sustainable systems such as the GRE pipes and unmanned aerial vehicles (UAVs).

7.9.1.1 Groundwater monitoring (GWM)

Groundwater is a natural water system fed by rainwater or snowmelt that seeps into the subsurface of the earth, depending on the soil type, land surface and rock structures in a given area (Rasouli Maleki, 2018; Anumalla et al., 2005). In the Niger Delta situation, groundwater formation does not include snowmelt as ice formation is not the geographical characteristic of the region. Porous surfaces such as sand and gravel allow easy groundwater seepage than less porous surfaces, hence less porous sedimentary surfaces such as the Niger Delta clay soil have the property of water retention and encourages flooding (Aich et al., 2016). An understanding of groundwater water table, saturation zones, permeability, porosity, aquifer's discharge, and recharge rates, etc. could provide the alert system that aid efficient adaptation planning and response in the regional oil/gas industry.

Groundwater is monitored for multiple objectives; evaluation of water quality, measuring the performance and quality of aquifers, analysis of underground water storage and depth of pollution caused by oil spills and sewage discharge (Anumalla et al., 2005; Berg et al., 2001; Green et al., 2011). GWM in the context of adaptation to climate change is the corroborative evaluation of groundwater fluctuation with the amount of rainfall (or forecast) that produces warning signs on the likelihood and magnitude of flood incidence. It involves the application of 'piezometer' technologies and wireless pressure sensors in measuring the rise and fall of water level in-situ (Krishan et al., 2014; Gaitanaru et al., 2017). It enables Assets Managers to plan and make a timely decision in the industry on how, when and with what is required to respond to flood events. GWM in the context of climate change adaptation has only received very scanty scholarly outlook globally including the Niger Delta basin drainage analysis systems (Feng et al., 2018). The emerging climate scenarios in the region prompted by the 2012 flood and the need for urgent adaptation planning has made hydrological studies and installation of flood alert system 9FAS) strategic and imperative.

7.9.1.2 Viewpoints Analysis

The study explores the viewpoints of some industry stakeholders in infrastructure management to underpin their views on GWM flood alert systems. Interviewees express adequate knowledge of the concept pointing at relevant GWM wells across platforms such as the Yokiri CCP/CPF Northbank sites. Generally, the NorthBanks estuary is 4.5 m above sea level and the CCP/CPF is about 800 m from the seashore, making constant GWM imperative. A respondent argued that:

"…in addition to the influence of the ocean and major river, there are other river tributaries (Orashi, Sombriero) that require the installation of gauges at strategic points. Now we know where we were in 2012 when the flood occurred. We use that as a benchmark to tell ourselves that we are approaching that crescendo and at such point, we must implement a certain level of those measures to either evacuate people, shut down some wells, flow station activities etc."

From the comment, 2012 flood seems to have exposed the absence of adaptation and flood emergency preparedness in the oil and gas industry in the Niger Delta; as lessons learnt have become benchmarking points for vulnerability assessment and planning. Knowledge of the 2012 gauge of the amount of rainfall and the times of tidal surge could further make a robust flood alert system that is dependable and reliable around critical infrastructures. Water levels measurement could be modelled to suggest optimal level as a benchmark for flood readiness plans.

In 2012, assets managers improvised water level monitoring system by using a special ruler marking technic implemented by fixing rulers at some distances from river banks to monitor surface water rising levels. This approach implies that there is an urgent need for a more scientific approach to surface water monitoring in the Niger Delta. A participant in an interview argued that

"… an improvised system for measuring the rate of the rising flood was used to engage and release responses according to the risk magnitude estimated from alert systems and weather forecast…if the benchmark is set at 12.6 m as alert rail, the danger level is considered from 11.5 m. The difference provides enough room to plan to begin from when the flood level reaches 9.5 – 10 m. Within this time, the necessary measures….to respond to a worst-case scenario are set. During the raining season, ERs are strategically triggered from 5 m level to 6 and 7 and so on…"

While improvised ruler monitoring technic can be improved, installation of piezometers in GWM wells at strategic locations in various platforms could further enhance the quality of the monitoring and accuracy of data on hourly rates (Feng et al., 2018).

More so, the telemetry water monitoring system stands as an alternative yet scientific approach available and could be implemented for flood and stormwater monitoring in the Niger Delta oil/gas industry (Tsigiroglou, 2008). Some of the merits of water telemetry as could be suitable for the study includes detailed, secured data integrated through internet network enabled access. It offers flexibility and long-term cost saving, remote access monitoring across a variety of vulnerable locations and eliminates manual/human deployment to vulnerable locations (Garcia, Retamar, and Javier, 2015). Nonetheless, there could be other demerits associated with the adoption of this system; it is not absolutely cost-free and requires technical expertise to effectively operationalise in the Niger Delta. Pending issues stemming from community interference with infrastructure and vandalism could constitute some of the regional unique challenges. Hence, assets managers could conduct a cost/benefit analysis and detailed risk assessment to ensure safe implementation and operation where this alternative is considered for the industry.

However, to ensure that adaptation plans are worthwhile, the prevalence of flood and other impacts need to be justified. A participant in the study claimed that *"Flood risks still exist into the future, with a magnitude such as recorded in September to October 2012 and other occurrences since then*"
This comment in addition to global climate projections and occurring events confirms the need for groundwater monitoring in oil/gas platforms. In 2012, the model indicated the highest groundwater level-up to 13.5 m above sea level (*Figure 65*) with a corresponding extreme flood activity. In the light of this, 11.5 m is set as the warning benchmark for the likelihood of severe flooding where emergency response decisions could be made. It is, therefore, necessary that GW is closely monitored at intervals in line with other complementary strategies such as sea level rise and water discharge rates to ensure that pragmatic responses are in place.

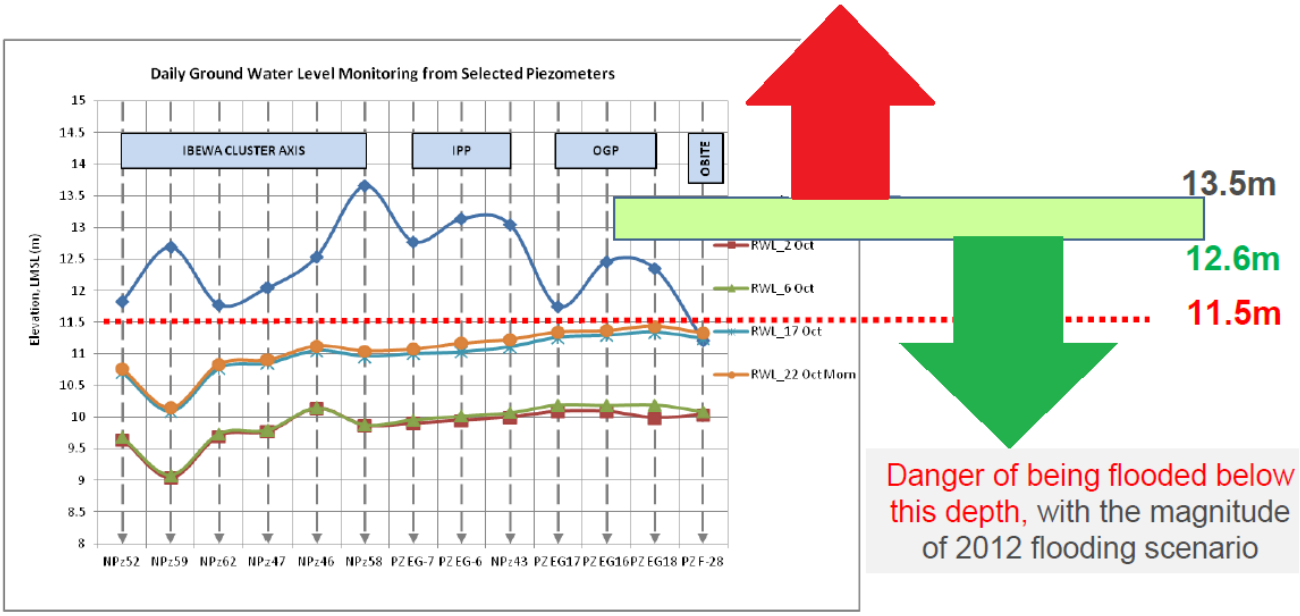

Figure 65; GWM model showing benchmark for flood alert. Source: Researched

7.9.1.3 Water Discharge Rate Monitoring (WDRM)

Water discharge rate monitoring or streamflow analysis is a hydrological measurement and evaluation of the volume of water discharged through canals, lakes, reservoirs, streams, tunnels, rivers, drainage channels etc. per unit time (Pant et al., 2016b). It is the measure of the area and velocity of water flow through a given section of a river in cubic metres/second (CM^3/s).

$$WDR\ (A) = av\ (cm^3/s)$$

Where; a is the area = dw

d = depth of the river and

w = width of river

v = is the velocity of moving water

WDRM, like groundwater monitoring, has been a significant tool for monitoring and analysing river/stream flow capacity, weighing the interconnections between surface and groundwater as requisites for effective coastal resources management (Pant et al., 2016a; Toonen, 2015). WDRM is initially initiated to understand the natural streamflow rate of rivers and their possible impact on coastal hydrology. However, it could be initiated as an adaptation measure in the Niger Delta to evaluate the increasing discharge rate and streamflow of water volume along the River Niger trough and other major distributaries. Since it is also used in evaluating the volume of water discharged from aquifers into river troughs, it provides an opportunity for aquifers along the Niger Rivers to be monitored. WDRM is initiated at intervals of stream flow and at the end of canals to reveal the volume of water loss or gained at any given time (Rasouli Maleki, 2018). Generally, streamflow data helps hydro-geologists to understand the sedimentation (seepage) properties of the river or coastal systems in predicting the scale of water flow that could result to flooding activities (LaBaugh and Donald Rosenberry, 2018).

7.9.1.4 Viewpoint Analysis

Accordingly, participants in this study did not demonstrate enough awareness of the implementation of WDRM as part of climate change adaptation in the oil and gas industry. However, the effectiveness of WDRM in climate adaptation depends on its efficiency in measuring both the rate of streamflow and the volume of groundwater system (Zhao et al., 2017b). This dual function characteristic of WDRM is an advantage for oil/gas industry in the Niger Delta because it negates the implementation of separate and restricted GWM systems, which saves time and financial implications, making adaptation more sustainable. Nevertheless, WDRM could also be limited to only infrastructures located along river troughs of onshore platforms, implying that GWM as adaptation mechanism is inevitable for onshore platforms but a combination, though cost-effective, could provide more accurate data on flood prediction and planning. The relationship between WDRM and flood occurrence stem from the conclusion that the higher the rate and volume of rising water in the river, the higher the likelihood of flood, relative to the nature of sedimentary systems of the river trough (Permatasari, Natakusumah and Sabar, 2017).

7.9.1.5 Analysis of the importance of WDRM in the Niger Delta

WDRM is a practical flood adaptation strategy for infrastructure resilience and oil and gas disaster preparedness in the Niger Delta. It is essential because;

1. Two principal water bodies (Rivers Niger and Benue) that influence flood activities in the Niger Delta, discharge unknown separate volumes of water at different rates that could cause emergencies down the Delta region (Badaru et al., 2014). WDRM could provide data on the rates of each river flow with the opportunity of evaluating and implementing case-specific solutions in-situ.
2. The two rivers produce unscaled water volumes at the confluence zone and flow unmeasured towards the Delta. Knowledge of each river seasonal flow volume could also affect focused planning at the confluence and Delta response to protecting critical infrastructures.
3. There are other minor rivers that discharge into the Niger trough after the confluence. This implies that WDRM is continued at reasonable distances along the Niger River trough up to the Atlantic to ensure that emerging volumes are captured and analysed critically.
4. Literature suggests that there are aquifers (groundwater systems) along the river distributaries in the Niger Delta that oozes water into the mainstream Niger River (Olobaniyi

and Owoyemi, 2006; Oseji, Atakpo and Okolie, 2005). Under rising groundwater system and heat-induced tectonic pressure in the Niger Delta, fragile aquifers have the tendency of discharging high volumes of water that could influence overall water speed as concurred in the position of Haile, Tefera and Rientjes (2016).

5. The hydrological sediments of Niger basin in Nigeria span over 28.3 percent of its 4,200 km overall coverage. This implies that the volume of water loss or gain varies along the river basin, hence in-situ monitoring may not produce accurate data for flood monitoring. Therefore, spatial WDRM systems are to be spread evenly along the rivers discharging into the major Niger basin to ensure that appropriate and maximum resilience responses are put in place.

From this analysis, WDRM is a suitable adaptation strategy for critical infrastructure protection in the Niger Delta and agrees with existing opinions on adaptation strategies in the coastal area and the impact of flood on critical systems (Pant et al., 2016b; J. Xu et al., 2009; Palmer et al., 2009; Wardekker et al., 2010). To effectively mainstream WDRM option, adequate analysis of hydrology of the Niger River trough is required before the installation of discharge rate monitoring stations in strategic locations. Modelling these data could provide overarching daily, weekly, and monthly signals of water volume in the River Niger. Decision makers could depend on this in planning an emergency response for critical infrastructure identified and prioritised in this study.

7.9.1.6 Construction and Positioning of Elevated Platforms (EP)

From this study, flood is seen as the most persistent climate-induced burden in the Niger Delta and has been confirmed in other coastal areas with low elevations (Haer et al., 2017; Hinkel et al., 2014; Nicholls, 2004). Elevation within locations of investigated critical oil/gas infrastructure in the Niger Delta is between 0.00 and 4.5 meters above sea level, while in 2012, flood water rose up to 13.5 meters above sea level in some locations. This indicates a high vulnerability and agrees with the findings of Wilby and Keenan (2012) who argued that inundated coastal areas are vulnerable to sea level rise and flooding. For continual oil/gas activities and operations in the Niger Delta industry up to the year 2100, recalibration and construction of higher platforms could accommodate the threats of the flood. Vulnerable systems in this context include all sensitive infrastructures built or installed on surfaces below reasonable sea level. For example, supply valves of the Northbank Central Compressing Plant and Central Processing Facility (CCP/CPF) shown in *Figure 65* is a typical example of vulnerable critical infrastructure from this study. This is because it is sited on the inundated platform only 4.5 m above sea level and about 800 m from the Atlantic shore. It could be recalled that 2012 flood incidence submerged systems up to 13.5 meters above sea level (*Figure 65*), implying that construction of high elevated platforms is critical adaptation and to sit preparation in the oil/gas operations in the Niger Delta. Locating the CCP/CPF on 4.5 meters above sea level is an indication of original vulnerability, which could have been avoided. This further justifies the absence of climate impact assessment in the industry which the conceptual framework arising from this study is highly emphasised.

Figure 66; showing inundated planned CCP/CPF located 4.5 m above sea level in Yokiri Northbank, Delta State. Source: Researcher

Some of the graphics obtained in this study show flooded EDGs and the entire Ogbogu Flow Station (OFS) and TEPNG OML58. Installing these systems on a broad-based concrete high elevated platforms (HEP) platform above 13.5 m above sea level or less with robust WDRM and GWM systems could have minimised the recorded impacts. All sites and locations including access roads to onshore oil and gas platforms require a realistic upgrade to ensure continuous operation during flood activities in the Niger Delta.

7.9.1.7 Construction of Flood Defences

Flood defences are often physical build up systems that protect critical areas and coastlines along water bodies from flood impacts (Dupuits, Schweckendiek and Kok, 2017; Hallegatte et al., 2013). This barrier (levees) system could be constructed in parallel or in multiple defence lines depending on the flood magnitude. Food defences wage against storm surges and river overtopping protected or general restricted areas (GRA) in the Niger Delta case. A typical double flood defence is illustrated below as an example.

Figure 67; typical flood defence illustrated by Source: Dupuits, Schweckendiek and Kok (2017)

A double flood defence mechanism is designed to cushion flood impact that exceeds a certain threshold. The front-line defence 'B' is designed to reduce the impact of flood load on the rear defence 'A', which contained spill water and jointly protect the building. Where the risk magnitude is low, a single defence or levee may be enough and subject to constant adaptive reviews in line with weather forecast and projections. Though double flood defences have financial implications and cost implications of adaptation alternatives is not covered in this study. The oil and gas industry has the capacity and responsibility to conduct a cost-benefit analysis and consider which alternative is best suitable in the Niger Delta scenario. However, due to uncertainty, flood defences are essential options recommended for operational oil/gas site to ensure that production is unhindered throughout the rainy season. Nonetheless, and where possible, multiple defence mechanisms could be constructed to provide resistance for the critical infrastructure prioritised in this study such as terminals, flow stations and transformers etc.

7.9.1.8 Construction of Buffer Zones, Reservoirs and Dams

In addition to flood defences, construction of artificial dams, lakes and reservoirs are some physical adaptation options that collect and store a large quantity of water from river basin to reduce its volume and capacity to cause flooding. It is argued that in Kansas District, USA, *"…dams are primarily built for flood control"* and Smithville Lake prevented about $1.6 billion USD damages to the critical downstream system from the flood (Grothaus et al., 2009). In the Niger Delta case, construction of reservoirs and buffer zones for water diversion and storage along the Niger and Benue rivers (*Figure 68*) could reduce both volume and flow speed during peak raining season. This is an essential adaptation measure to checking flood occurrence and impacts. Such reservoirs could provide sources of water for Agricultural purposes during the dry season and as water flooding for enhanced oil recovery (EOR).

Alternatively, buffer zones could be constructed at strategic locations around operational sites and platforms to divert runoff water efficiently and ensure a properly monitored protection of prioritised critical assets is in place. Brandt et al (2017) discussed the details and types of dams and their functions, which can be studied separately when this system of adaption is considered.

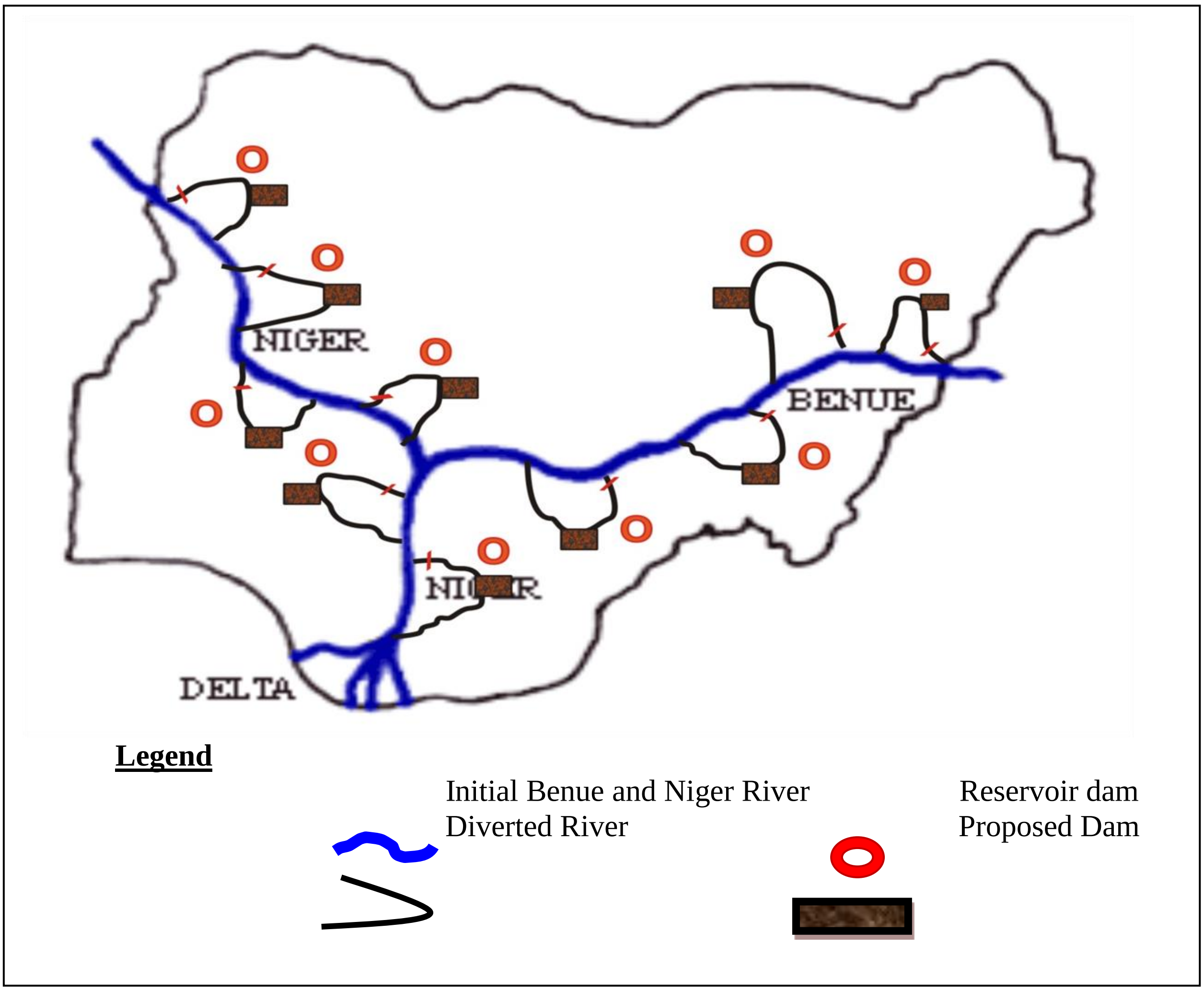

Figure 68; showing a model of reservoirs and dam that could be constructed along the Niger River to reserve water during high discharge rate and volume

7.9.1.9 Proper Channelization of Drainage/River Systems

In addition to river overtopping along the delta river banks, lack of proper channelization of drainages and rivers coupled with poor environmental management culture (improper waste disposal) by host communities are other vulnerability factors (Ologunorisa and Adeyemo, 2005). These encourage runoff water encroachment into environmentally sensitive areas and GRAs such as the case of OML58, OFS, etc. It is contended that long-lasting and stagnant runoff water could weaken and degrade infrastructure, delay operation resumption, orchestrate spread of water-borne diseases and paste during flood incidence (Trenouth, Gharabaghi and Farghaly, 2018). When improperly managed runoff water flood can overwhelm the resistance of critical systems, it results in operational activities being shut down pending recede of water. Channelization, speedways and drainage systems are practicable adaptation option that controls flood, increases the rate of water receding, and minimise impact. Stagnant water due to flood in some previous hydrological system has the tendency of raising groundwater level as it occurs in around a discharging aquifer. Flood water can be drained from within flood proof oil/gas operational facilities and community settlements through properly planned, designed, and constructed drainages (Tanaka et al., 2017).

7.9.1.10 Viewpoints and Analysis

This study argues that the impact of the flood on critical oil/gas systems in the Niger Delta context could cascade through to neighbouring social communities and systems such as forest reserves and tourism. It is observed that flood has submerged a once-popular beach located adjacent to Mobil producing Quo Iboe Terminal, Eket; one of the sites of the study area. The collapse of this tourism site amounts to pressure on Mobil in terms of being compelled to provide employment and extending corporate social responsibilities to accommodate the effects. A study participant confirmed extra cost on companies that;

"…when the host communities' loss cultural activities and occupations such as fishing, hunting, agriculture, and water shortage including accommodation and health facilities, the responsibility is passed on us and we are compelled to extend emergency response and resettlement programmes that stretches our initial corporate social responsibility boundaries"

Though the cost of stretched CSR was not stated, it however, implies that impacts of flood, for instance, directly or indirectly affect the oil and gas companies in the Niger Delta. Channelization and construction of drainage systems within platforms, networking communities is also capital intensive but could address the problem for about a decade or more. Participants in this study confirmed that if platforms and production sites were adequately channelized, *"…nine weeks delay in production on all affected fields operations in the Niger Delta during the 2012 flood incidence could have been significantly mitigated…"* In 2012, about 500,000 barrels of crude oil ($55.8 million USD) was lost due to flood. The incidence led to the declaration of force majeure (mandatory shutdown) of all affected fields (Tami and Moses, 2015) for which cost was not given. Construction of channels in operated fields and sites could have reduced the impacts and period of force majeure.

While participants in this study argued that incorporating communities in flood disaster planning is usually complicated, it also *"…stretches corporate social responsibility and have a severe impact on our flood accounting systems"*.

Nevertheless, the effective town planning system through construction and channelization of enhanced drainage systems (*Figure 69*) could increase assets and community resilience to flooding, impacts of tidal waves, and river overtopping (Trenouth, Gharabaghi and Farghaly, 2018; Mahmood et al., 2017).

Figure 69; a typical enhanced water channel draining runoff water

7.9.1.11 Substitutional – GRE, Stainless Pipes and UAVs

From the study, pipelines are often not impacted by the flood but are being subjected to rapid corrosion due to a mix of rising temperature and saltwater intrusion. In addition, the use of human elements in Environmental motoring in dangerous situations and circumstances is also substitutable with Unmanned Aerial Vehicles (UAVs). Hence, special adaptation strategies bothering on substitution are suggested for the industry. In recent global times, corrosion is being blamed for plant shutdown, health and safety challenges, intensive repair cost and loss of production in the oil/gas industry (Bahadori, 2014; Nutty, 2010). This challenge can be addressed by substitutional adaptation strategies where alternative systems are applicable. Substitution is the replacement of vulnerable infrastructures with a more sustainable alternative, which has the capacity to perform similar operations efficiently and effectively without being overwhelmed by prevailing climate-induced conditions such as flooding, corrosion, etc.

However, (Nutty, 2010) stressed that the negative effects of corrosion imply a high cost of maintenance and litigations for the oil and gas industry. He contended that the world corrosion organisation (WCO) has estimated the annual cost of corrosion of global critical infrastructure at $2.2 trillion USD. Deterioration of reinforced concrete and cathodic systems is highly influenced by CO_2

emission and ambient climate conditions such as temperature and relative humidity (Bastidas-Arteaga et al., 2013). They argued that since temperature changes are linked to climate change, substitution of cathodic and carbon steel systems is critical in areas that are being influenced by prevailing burdens. Some of these substitutional alternatives are discussed below:

7.9.1.11.1 Use of Glass Reinforcement Epoxy (GRE) Pipes:

As a means of adaptation, vulnerable (corrodible) carbon steel pipes could be substituted (replaced) with glass fibre-reinforcement epoxy (GRE) or glass fibre reinforcement plastics (GRP) pipes. GRE or GRP are pipes made from two reinforced materials (glass and plastic fibre) with the combined aim of achieving corrosion resistance. Bastidas-Arteaga et al (2013) affirmed that these technologies can counter the impact of corrosion induced by high climate change factors.

Figure 70; showing the use of GRE pipes in oil/gas terminal. Source: (Stangeland Glass Fiber Producer, 2015)

7.9.1. Analysis of Advantages

The advantages with GRE/GRP pipes include high resistance to corrosion and abrasion effects by transported debris during flood events. They are lightweight and thin-walled structured for ease of movement to and from different terrains suitable for onshore platforms (Abdul Majid et al., 2011). These properties indicate a reduction in the cost of transportation and installation of GRE pipes in rare locations where a swampy and marshy environment of the Niger Delta exploration stand at an advantage. Other advantages include their smooth inner surfaces that reduce friction with the transported material, an indication of long-lasting life and reduction in the cost of maintenance (pigging). More so, GREs possess the stiffness required to cope with high temperature and pressure from transported crude materials when applied in the oil and gas industry. It is also believed that the installation of GRE/GRP pipes is possible regardless of the climate and they have a service life extending beyond 50 years (HOBAS Worldwide, 2018). However, GRE pipes have some disenabling properties; materials for reinforcement are from both glass and plastics making hybridisation cost intensive. Compared with the scale of the industry and coverage by pipelines along the oil/gas asset value chain, there is a risk of cost could obviously limit to the implementation of GRE pipes. Contextually, GREs could be deployed in the construction of insitu infrastructures such as refineries, storage systems, and shorter distances as shown above but intensive usage could be very challenging in the industry. More so, lack of skilled manpower by local contractors in fabricating and installing GRE pipes could further discriminate spread of the innovation in the industry and further exposed the Niger Delta to climate threats. Therefore, a holistic approach – training, value chain analysis and investment are required.

7.9.1.11.3 Use of Duplex Steel Pipes

Duplex steel pipes (*Figure 70*) consist of about equal quantities of austenite and ferrite, which could be a favourable mechanical advantage property for corrosion resistance and against stress cracking. These properties are adaptable to heat exchange and suitable for ocean engineering works in the oil and gas industry (Wang, Ma and Li, 2011). Though there are concerns with steel fatigue, stress and distance of material transport, possible implementation of duplex pipes in the oil and gas industry seems to have gained popularity over carbon steel and the relatively new GRE systems due to rapid corrosion of carbon steel pipes associated with global warming (Charles, 2008; and Baddoo, 2008). More so, the high cost of commercialisation of duplex pipes could form another fundamental setback.

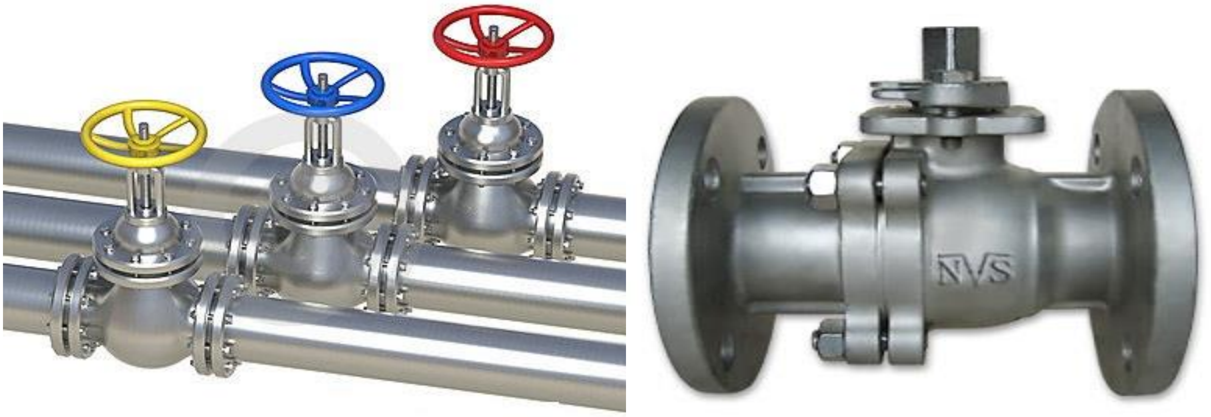

Figure 71; transporting steel trunk lines and valves. (Valtech Technologies, 2012)

7.9.1. Analysis of Advantages

It is argued that steel materials are a better substitute because of their high resistance to all forms of corrosive media prevailing in both onshore and offshore operations. They are resistant to chemical reactions such as temperature catalysed, low pH effects and stress of cracking (Wang, Ma and Li, 2011). Chloride is suspected as a major component of salt water that corrodes cathodic infrastructures in the Niger Delta, hence the need for substitution. Duplex steel pipes are preferred in the oil and gas industry because of their purported environmental compliance properties (Charles, 2008). As earlier contended, coping with the pressure of crude capacity could hinder suitability but could overcome rising temperature from the material load, but could suffer the impact of erosion, flood, that has potential to distort installation depths of systems (Akisanya, Obi and Renton, 2012). However, the scale of pipelines in the oil and gas industry is enormous as much as the cost of duplex steel pipes. The cost of purchasing and installing duplex pipes in commercial scale could be cumbersome and challenge the adaptation and sustainable choice. It, therefore, requires case specific critical cost benefit analysis probably backed by government policy to convince stakeholders in the Niger to swap carbon steel for duplex steel materials. Nonetheless, the reality of losing production and the cost of environmental pollution could urge operational international oil companies to invest in steel made pipeline infrastructure. But the weakness of Environmental Legislations in Nigeria and complaisant disposition of DPR Staff could thwart enforcement and implementation of steel pipes in the Niger Delta Context.

7.9.1.11.5 Use of Unmanned Aerial Vehicles (UAVs)

Some major industrial activities impacted by climate-induced weather are aerial environmental monitoring, flood monitoring and site view assessment. Weather events such as rainfall, flood and the cost of aerial surveillance are increasing across the globe and subjecting human life to more danger (Cruz and Krausmann, 2013; Mejia-Dorantes, Paez and Vassallo, 2012; Karl, 2009). UAVs are an innovative adaptation approach for monitoring complicated environmental situations including disasters such as blowouts, flash flood and spills (Perks, Russell and Large, 2016). NOC could demonstrate sustainable monitoring approaches for impacts and performance of affected infrastructure using UAVs (Shukla and Karki, 2016). Failure to acquire accurate data on flood impact through real-time monitoring in the 2012 flood incidence in the Niger Delta was blamed on the absence of effective monitoring systems. Conventional monitoring systems have proved inefficient and said to have exacerbated the severity of flood impacts on critical infrastructure in the Niger Delta. On the contrary, aerial flood monitoring using UAVs was implemented in the Houston Flood incidence in 2017 hurricane Harvey as indicated in Erdelj et al (2017) and Popescu, Ichim and Stoican (2017) work

Figure 72; showing the application of UAVs (drone tech) in flood recovery effort in Houston. Source: (Bold Business, 2017)

It is reported that "Extraordinary measures [were] being tested in the recovery process…[and] drone technology…was used by government agencies and businesses for large-scale surveillance and recovery efforts for the first time in history" (Bold Business, 2017). This example demonstrates the effectiveness of the UAVs in flood surveillance and recovery which is applicable in the oil and gas industry.

7.9.1. Analysis of Advantages

Though helicopters have been used for aerial surveillance, emergency response and rescue, their operations in complicated flood scenario, especially mangrove coastal areas of the Niger Delta could be technically challenging, costly and exposes emergency responders to danger (A. Shukla and Karki, 2016; Klemas, 2015). Implementation of UAVs in flood monitoring is economical, less complicated, low risk and essentially innovative strategy for mapping the extent of the flood during and after flood events. Implementation of UAVs in flood monitoring is an effective approach for determining the cost of insurance on companies. Implementation of UAVs is essential because a respondent suggested that

"…flood water in the Niger Delta is characterised by dangerous reptiles, submerged high tension cables, roads, bridges using human factors in both pre- and active monitoring spill monitoring during flood event exposes personnel to risks and fatalities"

From the quote above, flood does not only impact critical infrastructure, but it is also associated with threatening biological circumstances including oil spill and dispersion into sensitive ecosystems such as fresh water, groundwater and arable land systems. This is unsafe, non-sustainable and disregards the people, environment, assets, and reputation (PEAR) management ethos of oil/gas companies operating in the Niger Delta.

Unmanned Aerial Vehicles (UAVs) are operational innovative alternative technologies that have the potential for a safe, efficient and effective strategic flood monitoring system. Though UAVs have been applied in conventional environmental monitoring and aerial surveys, scanty scholarly work has been conducted on the implementation of UAVs technology in the oil/gas industry globally. For example, Algerian El Merk onshore oil/gas facilities located in the inhospitable desert was fundamentally constrained in terms of deploying equipment for secured environmental monitoring (Shukla and Karki, 2016); hence the need for aerial vehicles surveillance. Also known as unmanned aircraft systems (UAS), UAVs have been successfully applied in monitoring flood impact in metropolitan areas surrounded by large-scale hydrogeological basins and produce accurate images related to the extent of the flood (Abdelkader et al., 2013). It is claimed that in the wake of global warming, high demand for innovative technologies such as the UAVs in disaster monitoring, analysis, and preparedness will provide the advantage needed in monitoring sensitive coastal areas (Klemas, 2015). With this, oil and gas companies in the Niger Delta will find this report useful.

UAVs are being engaged in the assessment of damages, critical searches in rescue operations and examination of the extent of damages on critical infrastructure such as cell towers, roads, rails etc.

Similarly, UAVs can be used in the assessment of impacts of storm activities on critical infrastructures such as bridges, electric lines, and roads; more safely and faster than direct human effort in difficult and dangerous locations (Bold Business, 2017).

Effective adaptation alternative for flood monitoring and recovery in the Niger Delta oil/gas industry is possible with the application of UAVs. The deployment of human personnel and helicopters can be substituted sustainably with an innovative mechanism that provides effective and efficient surveillance system with as low as a reasonable risk level. Unmanned aerial vehicles or "drone's technology," could enable the industry to cope with climate change-induced disasters and impact in the Niger Delta. UAV technology has been contended to have the mechanical efficiency to produce timely and high-resolution images like helicopter-based satellite imagery. This makes UAVs appropriate substitute for the helicopter-based approach in the Niger Delta situation. Some of the infrastructure assessed in the Houston flood incidence implementing UAVs (roads, bridges and electric energy facilities) are incidentally prioritised in this study as vulnerable critical systems. This implies that application of UAVs in the Niger Delta to monitor Pipelines, Roads/Bridges, High Voltage Electric Cables, Flow stations, Terminals, Wellheads and Loading bays; during flood could be an ideal strategy. However, critical systems such as the high voltage cables (HVC) could adapt to different forms of protection to reduce the overall risks and delimit the use of other mechanical approaches. Apparently, the coating of high-tension electric cables though comes with an additional cost but could make UAV redundant in the Niger Delta situation given that there are no UAV legislations in place.

Nonetheless, there are ethical concerns and legislation by federal aviation authorities regulating the operation of UAVs, which may constitute some hindrances and create bureaucracies in obtaining licenses and permits to fly. However, oil and gas companies have the capacity to obtain all statutory permits and training required to fly drones for the protection of critical infrastructure. More so, oil/gas operations in the Niger Delta are mostly joint venture between the National Oil Companies (NOCs) and International counterparts (IOCs). This implies that government agencies could fast-track licencing procedures to ensure that economy revenue is secured by protecting critical infrastructure. For example, flying drones was initially banned in Houston until the impact of the flood from Hurricane Harvey challenged all essential monitoring systems and leave the authorities with no option other than implementing UAVs (Bold Business, 2017; Freeman and Freeland, 2014; Farber, 2014; Bold Business, 2017). More investigation is required to scope prevailing legislations before application in the Niger scenario.

7.9.2 Strategic Adaptation

Strategic Adaptation is an institutional based climate adaptation that aims to draw up plans on investment, divestment and implementation of core objectives of institutional decisions. From this study, the spatial impacts of climate change in the Niger Delta are attributed to interdependence and linkages of infrastructure as described by Bloomfield et al (2017); Zimmerman (2006) and Rinaldi, Peerenboom and Kelly (2001b). Accordingly, spatial adaptation planning is therefore expected to converge stakeholder views at institutional levels and share data related to critical infrastructure protection and emergency response within or with external partners (Eikelboom and Janssen, 2017). In the context of this study, relevant stakeholders expected to actively engage in an integrated climate adaptation discuss are; oil/gas companies (NOCs/IOCs), Nigerian Meteorological Agency (NiMET), Nigerian Hydrological Service Agency (NIHSA), Department of Petroleum Resources (DPR), the Government (Local, State, and National MDAs), the National Assembly (Policy Makers) and the Private Sector (Banks, Stock Brokers, etc). Others may include local waste management agencies, civil society organisations and NGOs, and Local Community leadership.

From the 2012 and preceding experiences of flood, rising temperature, heavy rainfall and storm surges, there is an urgent need for the Niger Basin Climate Change Adaptation Framework to be developed at regional stakeholder's forums drawn from Cameron, Guinea, Mali, Nigeria, and Niger, for the protection of coastal infrastructure along the River Niger. In this study, institutional adaptation is decomposed and analysed in different strategic strata to ensure that adaptation theory is targeted, effective, participatory, and deliverable by all the stakeholders at internal and external organisational collaboration (Burton, 2016).

7.9.2.1 Internal collaboration

This is aimed at developing a sectoral strategy that pulls together efforts of oil and oil servicing companies such as Total Exploration and Production (TEPN), Shell Petroleum Development Company (SPDC), Mobil Producing, etc. to undertake the responsibility of deciding how to address climate impacts in the industry. A participant in this study expressed concern over enduring extreme climate impact in the industry claiming that:

"We at the industry expressed more concern because we were the major victims of the 2012 incidence…so we have learnt our lessons. We make sure we track, monitor and provide first early warnings and implement measures already identified, to prevent escalation"

This implies that the lesson from 2012 has created a boost for internal adaptation to be developed in the industry at specific levels. Ultimately, internal collaboration would underpin frontline approaches for immediate protection of critical and sensitive infrastructures, without the initial engagement of other organisations. In the Niger Delta situation, internal collaboration is expected to be holistic encompassing all departments but with a programme director to manage the discussion. Possible departments such as Asset Management, Environment and Industrial Hygiene or Quality Health and Safety (QHSE), Operations, Logistics, Legal, Security, Research and Development, Account, and Human Resources and Community Relations could form internal collaborative climate adaptation programme. The leadership of internal collaboration lies in the Management who ensures that all departments deliver their specific role binder on a day-to-day basis to ensure that programme objectives are met. Internal collaboration is the first step towards climate adaptation planning where organisations independently overhaul private assets through sensitivity, vulnerability and criticality evaluation with the aim of building immediate resilient structures against climate impact (Jude et al., 2017).

Internal collaboration at strategic levels may include the following plans:

1. Installation of flood alert systems through GW and WDR monitoring
2. Implementation of alternatives (substitutes) infrastructures such as GRE/GRP, steel pipes and UAVs
3. Channelization and construction of drainage systems within operational platforms
4. Elevating operational platforms and linked critical infrastructures
5. Construction of in-situ water reservoir and buffer zones
6. Sponsorship of scholarly investigations on the hydrology and meteorology of the Niger Delta
7. Prioritisation of adaptation strategies
8. Installation of alternative sources of energy such as microgrid PV systems and steam; on sites to substitute for EDGs and transmission systems
9. Annual review of assets management reports and evaluation
10. Designing an effective mutual assistance plan (MAP) with sister organisations ahead of external collaboration
11. Organise flood awareness drills, internal forums, and workshops to discuss organisational plans with all staff, visitors, contractors, and shareholders.

However, internal departmental collaboration has been criticised for having some disenablers. Foremost is its lack of broad-based strategic framework and possibilities of inconsistencies arising from decision-making in the selection of alternative adaptation options (Burton, 2016). In line with the argument, this study has provided a conceptual framework and demonstrated the systematic application of AHP in converging multi-stakeholder opinions in making choices from various alternatives. It eliminates controversies and counter decision-making that prevail in conventional voting that often results in inconsistencies. Also, internal collaboration may lack the required expertise and technical authority to effectively engage and analyse climate change adaptation in line with international best practices. Therefore, individual oil/gas companies in the Niger Delta could employ the services of a knowledgeable and technical consultant to advise on the internal strategies in terms of implementation review and improvement.

7.9.2.2 External collaboration

This involves the participation of stakeholders from all relevant organisations with an intersecting mandate in climate change adaptation and mitigation planning and implementation processes. In addition to NiMET, NIHSA, NNPC, Civil Right groups, Federal and State governments, other relevant collaborators may include the Academia, Media and Telecommunication, and the Transport industry. An Integrated Climate Change Disaster Management (ICCDM) group could be formed from the multi-stakeholder coalition. In this context, oil and gas multinationals are expected to play the leading role in reawakening other stakeholders in this strategic collaboration to ensure that decided outcome minimise the impacts of extreme events on critical infrastructure and communities. External collaboration potentially triggers spatial response to climate change at all responsible corporate levels to ensure that productivity is optimised, and critical assets have the resilience and resistance to withstand extreme environmental burdens. External collaboration apparently reduces the chance of conflict and litigations often associated with communities and government agencies against oil companies in cases of oil spill and pollution (Ifelebuegu et al., 2017; Emoyan, 2008).

In the Niger Delta context, an external collaboration of multi-stakeholder adaptation programme may capture the following among other objectives:

i. Improving corporate communication between agencies of government (such as NiMET, NIHSA, academia, communities, etc.
ii. Establish effective International Corporate Communication (ICC) mechanism with the management of Lagdo and related Niger Basin dams
iii. Establish an effective data sharing model to ensure relevant information get to relevant stakeholders on time for preparedness and safe evacuation
iv. Establishment of the Niger Basin Climate Adaptation Programme involving countries within the Niger Basin such as Cameroon, Mali, Guinea, Nigeria, etc.

v. Development of strategic integrated climate emergency response plans
vi. Proposed collaborative research programmes on climate forecast, modelling, and cost benefits analysis of adaptation programmes
vii. Organise annual conferences on climate change mitigation, adaptation, and best practices for scholarly sharing of emerging ideas
viii. Contribute to the adjustment of Environmental policies
ix. Suggest and encourage adaptation investment, and implementation of strategies
x. Participate in the annual review of adaptation plans and suggest strategic improvements
xi. A design framework for local community engagement (on attitudinal change, waste management training and practices, environmental enlightenment campaigns programmes)
xii. Actively participate in designing town planning codes with relevant government agencies
xiii. Encourage realistic technology transfer, equipment sharing and personnel support system
xiv. Providing timely flood warnings with follow up response approaches
xv. Collaborative desilting of drains and canals to allow free flow of runoff water at peak seasons
xvi. Design safe evacuation routes for communities in coastal areas
xvii. Design and promote local strategic flood prevention plans and annual vulnerability assessments
xviii. Building institutional capacities by equipping Emergency Management Agencies at both state and Federal level (NEMA, NiMET, and NIHSA) and encourage regular flood emergency response drills and training at institutional levels.

The rationale for the suggested list of objectives is to highlight possible aims of strategic engagement with stakeholders and variable expert and interest level for effective adaptation. This approach has been used as intergovernmental collaboration in developing environmental resilience in the Pearl River Delta of Southern China and long-term adaptation capacity building in Albay, the Philippines (Hartley, 2018; Cuevas et al., 2016)

7.9.2.3 Community Awareness/Enlightenment

One principal approach to reducing the impact of flood, storms and seawater intrusion in the Niger Delta situation is intensive awareness and public enlightenment campaign in host communities. Pragmatic environmental sensitisation approach with an efficient environmental management plan, which incorporates effective waste management strategies in communities is required (Pearce, 2003; Madumere, 2017). Community involvement in critical infrastructure protection and climate adaptation is crucial in the Niger Delta case because of the historical narratives that suggest active social unrest orchestrated by host communities in disrupting oil/gas activities (Kadafa, 2012; Anifowose et al., 2012). Adaptation actions that lack encompassing coordination across sectors are likely to trigger conflicts, competition, and degradation of natural resources. More so, industry or sector-specific adaptations often shift climate change impacts on future generations other sectors and failed to provide community-wide resistance and resilience (Koopman and Graham, 2018). Hence for adaptation programmes in the Niger Delta to be effective, experts and practitioners will include communities, all relevant stakeholders and groups, equipping them with applicable adaptation tools through a public participatory explicit, collaborative, and encompassing decision-making process. Where necessary, experts could provide training needs on emergency response systems.

This collaboration should consider the socio-economic and geopolitical data of the region while ensuring that adaptation approaches are not ambiguous, but flexible, cost-effective and sustainable. In agreement, Ologunorisa and Adeyemo (2005) concurred that flood control in the [Niger Delta] region requires active but simplified tasks for multi-stakeholder participation by the government, the media, local community and NGOs, through efficient environmental enlightenment campaigns. With successful community participation, information and coordination of regular desilting of drainage systems and behavioural change are expected to ensure that domestic waste and debris are properly managed.

7.9.3 Emergency Response (ER) Adaptation

With the frequency of flood and other climate-related extreme events, emergency response services need to update and upgrade to adapt effectively to the changing situation in the Niger Delta. According to Levy et al (2007) flood disaster emergency responses are complicated events that require a holistic interdisciplinary response that involves all partners in disaster management. However, collaborative flood disaster response in the Niger Delta situation requires significant training due to the terrain and sensitivity of the oil/gas systems. Flood in sensitive areas with storage tanks interconnected with high capacity crude-carrying trunk lines and high voltage power cables makes it highly risky and unsafe for non-expert personnel operations. Usually, POB are trained and permitted to work in sensitive areas to minimise the risks. Oil spill has severe health and environmental implications for human health and safety Grattan et al (2011). Hence, emergency responders in the industry require adequate professional training and regular drills before deployment. Internal and external expert collaboration is desired in the industry for equipment sharing and partnerships. The broadness of collaborating organisations needs careful consideration to minimise conflicts of interest and technical priorities during emergency response as it is argued that qualified experts could have professional relationships that could trigger a conflict of interest (Billi et al., 2005). This study has presented a systematic approach to managing conflicts in decision-making involving multi-stakeholder practices also used by Levy et al (2007) in flood hazard and emergency management.

7.9.3.1 Stakeholder Viewpoint and Analysis

In this subsection, some of the ER adaptations acquired from field investigations and interviews are presented from participants and theoretical viewpoints. It was confirmed that there are highly vulnerable general reservation areas (GRAs) in the forecast to be impacted in the Niger Delta oil/gas platforms which assessment is restricted to personnel with a permit to work. These areas have high risks of drowning, electrocution, severe injuries, and possibilities of multiple fatalities, hence, it is a highly restricted area that could interfere with a holistic conventional emergency response. However, such scenarios demand that UAVs systems are implemented to reduce the risks arising from human exposure. Selected ER adaptations for critical infrastructure and community protection in the Niger Delta may include;

a. Publication of early warning signs and alerts among all stakeholders
b. Safe and timely evacuate of POB and communities
c. Securitisation and waterproofing of all sensitive systems such as EDGs
d. Providing engineering control for sensitive assets to avoid social attacks and debris collusion
e. Provision of stand-by floatable boats and life vests for emergency evacuation
f. Maintain and unblocked all drains and deploy booms around the perimeter fencing, pits, and storage tanks
g. Relocate all harmful chemicals from floodplains and construct alternative secured storage systems
h. Update sight contingency plans to include possibility of flooding and drowning scenarios
i. Conduct a climate vulnerability studies of site environment, drainage systems and hydrology
j. Maintain some stock of live boats and other accessories (Plan alternative systems to cushion the effect when existing systems are impacted)
k. Provide depth markers on site for flood checks
l. Organise periodic flood drills to keep responders and stakeholders alert

7.9.4 ER for Electrocution

These are responses expected when storms or flood tend to submerge high tension electrical cables and other engines that could leak electrical power outside insulated space. Should this occur, responders are expected to:

a. De-energise and isolate electrical systems
b. Shutdown engines and notify external grid suppliers for further action
c. Control unauthorised persons from entering GRAs and waterproof (coat) all electrical structures

7.9.5 ER for Host Communities

The following adaptation responses are suggested for local community mobilisation during extreme weather crisis in the Niger Delta context:

a. Identify alternative safe havens within the area for community resettlement – should be areas with recommended elevations
b. Provide emergency social services such as toilets and potable water
c. Set up an ER medical team(s) in makeshift settlements
d. Provide secured social facilities such as mosquito nets, mobile toilets, etc
e. Conduct thorough fumigation of areas to prevent pest and dangerous creeping insects
f. Devise an effective means of waste management to avoid further contamination and pollution
g. Conduct water quality examination to ensure that available water is safe for drinking otherwise seek alternative sources of water in camps
h. Cancel all visits to flooded sites and operational platforms
i. Set up Emergency Command and Control Centre (ECCC) to ensure adequate security of lives and property
j. Prepare, keep, and monitor a checklist of people, activities, and procedures regularly

7.9.6 Recommended Recovery Programmes

Though these recommendations are not the main focus of the analysis and study scope, flood responses often require recovery process that pose significant challenges for the industry in the Niger Delta. The recommendations are additional researched best practices and added to strengthen the study outcome and make an encompassing report for industrial usage (Wilby and Keenan, 2012;

Kuklicke and Demeritt, 2016; Perks, Russell and Large, 2016; Dupuits, Schweckendiek and Kok, 2017). Site preparation to resume operation, resettlement of communities and building of camps, environmental clean-up approaches, water screening and investigations by insurance companies, etc are part of the recovery processes. Some crucial recovery programmes to be implemented include but not limited to:

i. Update sight contingency plans to include flooding and drowning scenarios
ii. Provision of sand backs to demarcate roads and sensitive areas
iii. Continue periodic flood drills for both company personnel and host communities
iv. Review all alert systems and implement recommendations
v. Relocation of critical systems that are consistently impacted if possible
vi. Maintain some stock of live boats and other accessories on site
vii. Plan alternative production approaches to cushion the impact
viii. Provide depth markers on site for flood checks
ix. Measure and record site elevation and recommend climate impact assessment report from all contractors on resettlement planning.
x. Produce a comprehensive report of the incidence and publish the same for further use

7.10 Chapter Summary

This chapter suggested climate adaptation strategies for implementation in the oil and gas industry for critical infrastructure resilience and resistance in the Niger Delta. Resistant adaptations are said to be self-proof systems built around a critical asset such as Flow stations and Terminals; to optimise all year-round operations regardless of impact magnitude. Resilient systems are infrastructure that maintains their engineering integrity after impacts. Justification of the need for adaptation in the Niger Delta case is discussed in detail with analysis of stakeholder viewpoints to buttress the urgency required to implement these strategies. Three main themes of adaptation are covered:

1) Physical adaptation – involving groundwater and water discharge rate monitoring to provide flood alerts and specific emergency response levels in the oil and gas industry, construction, and installation of systems on high elevation platforms, and construction of flood defences, buffer zones, dams, reservoir and channelization of drainages and rivers. Substitution of carbon steel pipes with glass reinforcement epoxy pipe and duplex aluminium pipes is also presented in addition to the implementation of unmanned aerial vehicles, UAVs (drones technology) in flood monitoring. UAVs are argued to provide sustainable and innovative monitoring of assets performance and the extent of the flood with the view to eliminate the risks of human involvement and reduce the cost of helicopter aerial monitoring and evacuation.

2) Strategic (Institutional) adaptation - entails active collaboration of relevant stakeholders in the management of climate-related risks such as the predominant flood. Internal collaborations encourage oil/gas companies to develop independent procedures and plans for climate adaptation while external collaboration emphasises inter-agency and organisational engagements with the aim of preventing critical infrastructure vulnerability. Community awareness is highly emphasised because the impacts of flood and other environmental disasters in the industry could indirectly affect social communities. Poor environmental and waste management behaviours and practices exacerbate the impact of the flood, hence the need for strategic plans through community enlightenment and awareness creation.

3) Emergency Response - When the inevitable occurs due to the failure of physical and institutionalised strategies, reactive measures are called to mind bear for an emergency response. Emergency response approaches are in-exhaustively suggested with focus on electrocution, and evacuation of host communities as the extra corporate social responsibility of the oil companies. Emphasis is also laid on securing sites from social attacks during flood and waterproofing of sensitive systems as much as possible to avoid electrocution.

Finally, specific recovery programmes are suggested for the industry. Though scientific details of these strategies are not provided, each of the approaches could be further researched and mainstreamed to improve critical infrastructure resilience and resistance in the Niger Delta context.

CHAPTER EIGHT
DISCUSSION AND IMPLICATIONS OF FINDINGS

8.1 Introduction

The main aim of this thesis was to assess the vulnerability of critical oil and gas infrastructure to climate change impacts in the context of the Niger Delta and suggest possible sustainable adaptation alternatives for critical infrastructure protection. The following objectives were identified and lead to achieving the research aim:

a) To review the potential impacts of climate change on oil/gas critical operations in the Niger Delta
b) To conduct an intensive review of the literature and develop a conceptual framework for vulnerability assessment of critical oil and gas infrastructures for the region
c) To identify critical oil/gas infrastructure through a systematic prioritisation process
d) To evaluate the vulnerability identified critical infrastructure to climate change impacts impact in the Niger Delta
e) To suggest sustainable and practical adaptation strategies for oil and gas infrastructure resilience in the Niger Delta

To achieve these objectives, the under listed research questions were proposed;

a) What are the impacts of climate change on critical oil and gas infrastructure in the Niger Delta?
b) What could the conceptualised framework be suitable for the investigation of climate change impact on critical infrastructure?
c) How could critical oil and gas infrastructure be identified for vulnerability assessment in the Niger Delta?
d) How could critical infrastructure be systematically prioritised based on vulnerability to climate change in the context of the Niger Delta?
e) What are the possible adaptation strategies for critical vulnerable infrastructure protection in the region?

Hence, this chapter combines the discussion and implications of findings which present how the contributions of research – a framework for vulnerability assessment and other results; could excite critical thinking on climate change impacts on oil and gas business and adaptation in the Niger Delta as could be applied in other relevant locations globally. Section two, on the other hand, elicited the achievement of the thesis objectives, major findings and implications, contributions to knowledge, limitations and recommendation for further studies.

In the result and analysis chapter (criticality, vulnerability, and documentary evidence sections), some elements of the result were discussed to illuminate the implications of research outcome. In this chapter, further discussion is concisely presented to avoid repetition. The emerging cases of differential flood impacts on Chevron and TOTAL OML58 platforms and the disruptive impact of rising ambient temperature on Ogbogu Flow Station's separators and compressors are also discussed. Discussion of the two cases aimed to further advance the argument of evidence and impact of climate change on critical infrastructures. This is to strengthen adaptation investment argument in the industry. The discussion is structured in the following order in addition to the introduction:

i. Commercial implications of findings in other industries
ii. Implication and potentials for implementing research framework
iii. Selection of critical infrastructure
iv. Selection of vulnerable infrastructure (vulnerability assessment)
v. Implications of suggested adaption and the PEAR strategy
vi. Emerging issues of vulnerability and adaptation from the investigation and
vii. Summary of the chapter

8.2 Applicability of Findings in other industries in the Niger Delta

As noted by Kröger (2008), prevailing climate-induced extreme weather could significantly impact critical infrastructures such as energy, telecommunication, transportation as well as other living conditions in the coastal Delta. Literature from other researchers in the Niger Delta corroborate these assumptions suggesting that the coastal Niger Delta is being severely impacted by the flood, winds storms and other anthropogenic climate changes risks (Udie, Bhattacharyya and Ozawa-Meida, 2018; Tami and Moses, 2015; Nzeadibe et al., 2011; Aloysius, 2012). Consequently, these industries require urgent vulnerability assessment and adaptation planning to minimise the risks and could accordingly, benefit from the framework developed in this study. Prevailing climate-related extreme conditions identified in this study include heavy and frequent rainfall accompanied by wind and thunderstorms, rising sea level and the Atlantic tides and increasing temperatures. These conditions occur at an extreme level with severe impact on sensitive transport, telecom, social and oil and gas infrastructure in the Niger Delta (see section 6.4.6 Probable causes and Impacts of OML 58 Flood). These effects have in recent times caused irregular emergency shutdowns of systems and evacuation of personnel on sites, exacerbated oil spills, assets disruption and corrosion. Accordingly, Dana Air a popular commercial airline operating in the region (Port-Harcourt, River State), was recently impacted by a severe storm. Though this incidence could be argued as once in time events, the frequency of such events across sectorial systems calls to mind the issue related to climate change. Nonetheless, the figure below shows Dana's twitter handle corroborating extreme weather impact and blaming the incidence of severe storms.

Figure 73; showing twitter account of Dana Airline announcing impact of storm surge

Dana's claim above further confirms evidence of climate change impacts contended in this study and validated the proposition of Kröger (2008) that critical infrastructures are vulnerable to climate extreme conditions in the Niger Delta. Stormy weather impacts do not only affect commercial airlines business but cascade through to the oil and gas industry which relies on the frequent use of helicopters for the transport of personnel and services to both onshore and offshore platforms. Helicopters are commercially used in the transportation of personnel to and from platforms such as the OML58, Escravos, etc. Heavy windstorms could also affect scheduled access to non-motorable islands platform, aerial surveillance and security operations. Anifowose (2012) had argued that pipelines infrastructure in the Niger Delta suffers deliberate attacks; which could require aerial surveillance. This implies that the impact of stormy weather could affect aerial security operations and further exacerbate "interdictions" and oil theft.

8.3 Commercial implications of the Conceptual framework

One of the outputs of this study is the realisation of a conceptual framework for the vulnerability assessment of critical oil and gas infrastructure though in the context of the Niger Delta. This study outcome addresses objective two and question two of the overall research. To identify, select and prioritise critical infrastructure for vulnerability assessment, there are critical inputs segments that require careful attention. Because the assessment is a multi-disciplinary process, relevant stakeholders and decision makers are consulted on time to design a suitable strategy that complies with the ethical requirements of the research environment and justifies the research case. Three important segmented strategies identified in this study are scoping, vulnerability assessment and mainstreaming finding into expert-based implementation process (Udie, Bhattacharyya and Ozawa-Meida, 2018).

The framework was designed from the critical review of existing literature on strategies of conceptualising investigations related to vulnerable systems such as roads, telecommunication, financial and energy infrastructure from different parts of the world (ACT Government, 2012; Nelson et al., 2010; FHA, 2012; Burch and Robinson, 2007). Relevant literature suggests that the lack of vulnerability assessment in the oil and gas industry is blamed on the gap of a conceptual framework which experts and practitioners could rely on (Tami and Moses, 2015; Giwa, Adama and Akinyemi, 2014; Emoyan, 2008). To bridge this gap, this study framed questions and objectives that focus on achieving a flexible and applicable framework for the multidisciplinary assessment of critical oil and gas infrastructure in chapter one and developed in chapter three respectively.

The advantages of the framework are flexibility, replicability, and transferability from the oil/gas sector to other crucial sectors. It has three major segments; with each having intricate application pathways developed for easy use by both exert professionals and academic researchers and includes scoping, vulnerability assessment and mainstreaming.

8.3.1 Scoping

This section provides the formation of vulnerability assessment background in this study. It identifies the main aim and objectives, review of relevant literature and exploration of the research area which can be adopted for assessment in other industries. An explorational aspect of scoping provides the frame for interacting and selecting prospective research participants, identify the prevailing vulnerability indicators, climate burdens and ethical issues amounting to confidentiality in any relevant industry. A critical aspect of scoping captures infrastructures under construction are captured in the assessment process and analysed to ensure that adaptation strategies are integrated and ramified up to the design, fabrication and installation of critical infrastructure. From this study, other energy infrastructure such as geothermal, wind, and hydroelectric platform could be investigated with the aim of incorporating inbuilt resilience and resistance that could withstand the flood, storms, temperature and rising sea levels and tides. It implies that proper effective scoping investigation ensures that inbuilt resilience and resistant adaptation could prevent critical infrastructure from future climate impacts. In this study, scoping revealed the vulnerability of the Central Compressing Plant and Central Processing Facility (CCP/CPF) in Forcados-Yokiri Integrated Project (FYIP) Phase II in North-Bank estuary in Warri, Delta State; from its installation stage. The site Project Engineers confirmed the exclusion of climate impact assessment from the project installation site plan and design but affirmed the crucial need for vulnerability investigation.

Nevertheless, scoping as applied in this study context and contained in the developed conceptual framework is relevant and applicable in aviation, engineering, modelling, telecom and social researches; involving climate vulnerability assessments. Practitioners and researchers in other industries and sectors within and outside the Niger Delta region as proposed by Petrova (2011), Alcaraz and Zeadally (2015) and Pursiainen (2017) could apply scoping strategy as precedence to vulnerability assessments.

8.3.2 Vulnerability Assessment

Each segment of the framework has the potential of forming a standalone research proposal, implying that scoping, vulnerability assessment and mainstreaming could be independently researched with valid outputs. However, this study maintained an integrated assessment strategy where all the elements of the framework were demonstrated comparable to other investigations (Havko, Titko and Kováčová, 2017; Denner et al., 2015; Ouma and Tateishi, 2014; Yuen, Jovicich and Preston, 2013). Vulnerability assessment is the most crucial aspect of the research framework from this study. It is an iterative procedure that captures in-depth data collection and analysis implementing a suitable methodology such as the AHP. Other researchers may choose to apply the analytic network process, qualitative processes such as interviews and focus groups involving properly stratified participants. Experienced participants are likely to provide more relevant inputs and understand the research aim more than fewer experience participants (Harvey, 2010).

Vulnerability assessment involves ranking of critical infrastructure using acceptable criteria (indicators) arrived at from scoping where review of relevant literature occurs. These indicators are pairwise compared to measure their weights and understand how this could influence vulnerability. The outcome of these weighting could vary significantly if applied in different sectors where climate variability and impact is less significant but provides a roadmap for measuring the vulnerability and criticality of systems. In addition to the application of methodologies with suitable indicators, extra observational field assessment is recommended where experienced personnel are appointed to chaperon the investigation. Through physical observations, more data is acquired for the analysis phase. Critical analysis of triangulated data could be cumbersome and time-consuming. In this study, Mi-AHP tool was implemented to aggregate the opinions of participants. Researchers may choose to implement other software models such as “expert choice” in analysing result but this is expected to be integrated from the planning and design of the research. This combination has been implemented successfully by Ishizaka and Labib (2009) and Bayazit (2005). The outcome of analysis could be mainstreamed to provide needed long and midterm solutions in the industry. Researchers in the industry are expected to consider approaches for mainstreaming with the aim of addressing the empirical problem at very specific levels (Huq et al., 2004; Rauken, Mydske and Winsvold, 2015).

8.3.3 Mainstreaming

A prominent aspect of the framework is its aim to ensure that the outcome of vulnerability analysis from this research is mainstreamed into industrial practices. Mainstreaming has been suggested and implemented by researchers in oil/gas industry through the delivery corporate social responsibilities and found to be effective and efficient in addressing various challenges (Du and Vieira, 2012; Idemudia, 2014). The achievement of this research objective (design of a framework for vulnerability assessment) provides a handy instrument available to assets managers and experts to incorporate and operationalise in the context of critical infrastructure vulnerability assessment. More importantly, the opening for introduction of developing infrastructure in a framed research environment further justifies its usefulness in a holistic assessment.

Mainstreaming findings, mostly the suggested adaptation strategies in (see section 3.4.4 Mainstreaming) could restructure the asset management policy of the organisations with respect to emergency planning, disaster risks management and future assets prioritisation. This agrees with the proposition of Rauken, Mydske and Winsvold (2015) and Huq et al (2004) who confirmed the need for adaptation planning in developing countries from mainstreaming investigation results. From this study, the mainstreaming outcome could create more awareness across the industry on prevailing climate change risks, critical and vulnerable infrastructure. It is advised that while scoping is the entry point of the research framework, the endpoints do not exit the research. It rather suggests continual monitoring, reviewing and implementation through re-scoping, vulnerability assessment and mainstreaming – confirming the iterated nature of framework (Mehrotra et al., 2009).

Nevertheless, mainstreaming research investigation outcome is not limited to the oil and gas industry where this framework is applied. A systematic application of this framework in other sectors may present a valid result that could be mainstreamed for industrial application and critical infrastructure protection.

8.4 The potential for implementing Framework

The purpose of the research framework was to provide a sustainable assessment pathway for evaluating vulnerable critical infrastructure in the Niger Delta context and has been successfully applied through this study. It has the potential to address industry challenges and contribute to the following functions:

i. Replicability across the industry in other locations other than the Niger Delta
ii. The framework has become a supporting tool for experts and academics to engage in adaptation and mitigation planning in the industry
iii. The integration of analytic hierarchy process (AHP) tool has eliminated the possibility of controversies and conflict of interest arising from voting and expert's decision approaches
iv. It promotes participatory interdisciplinary research involving critical decision making
v. Its integration in the internal environmental management policy of oil/gas organisations or national government environmental guidelines for the petroleum industry in Nigeria (EGASPIN) could aim at protecting both the environment and businesses simultaneously.
vi. It has the potential to breed professionalism and best practice and a reference tool for other researchers with interest in the oil and gas industry and the Niger Delta critical infrastructure.

8.5 Framework Unique Attributes

The potentials of this framework depend on its unique attributes from design to implementation structure (Becker, 2005). Its most considered uniqueness is that it is being developed from practice – expert-based approach and review of relevant approaches, with data acquired directly from the field through interviews with properly stratified practitioners. This provides the assurance of its validity and reliability in eliciting data and analysis by both group and single user researchers. Thirdly, it explicitly described the integration of the chosen methodology and present the opening for substitution of methodology depending on the research circumstances and design. However, the framework poses some constraints in terms of the number of acceptable infrastructures per circle of investigation due to the limitations of the AHP. This implies that the framework is constrained in scenarios where there are several (more than seven) critical infrastructures for vulnerability assessment. Nevertheless, in such scenarios, segmentation (experts grouping) of scoped systems may be encouraged for independent group assessment (Swartz et al., 2003).

8.6 Selection of critical infrastructure

Critical infrastructure includes all virtual and physical assets that play an essential role in national development such that if disrupted could severely and negatively impact on national economic well-being, environmental and ecosystem sustainability, the safety of human life and interdependent systems (Alcaraz and Zeadally, 2015; Petrova, 2011; Karabacak, Ozkan Yildirim and Baykal, 2016). It is revealed that the dependability, operational status and performance, physical safety, and protection of critical infrastructures is a national priority for Nigeria and other nations globally as contended by (Alcaraz and Zeadally, 2015). This study successfully applied the analytic hierarchy process (AHP) in prioritising critical oil and gas infrastructure using indicators (Economic, Environmental, Interdependence and Human health and safety) identified in relevant publications. It is found that though oil/gas infrastructures are sensitive national assets, some are more critical in terms of the impact they could transmit if negatively hit by climate-related extreme events such as flood, high temperature, wind storms and heavy rain in the Niger Delta context. The successful hierarchical structuring of critical oil/gas infrastructure based on criticality address objective three and the third question of this study and provided an additional justification of the overall research aim.

The implications of evaluating indicators are that if critical infrastructures are disrupted, Economic well-being and Environmental systems could be most adversely affected by up to 39.54 - 37.06% of the impact magnitude while Interdependence and weak adaptive capabilities of infrastructure could exacerbate impacts by 13.8% and 9.60% respectively. This means economic wellbeing, environment, interdependence and weak adaptive capacities fosters severe impacts of climate change the economic as contended by (Elias and Omojola, 2015; Isma'il et al., 2014). The outcome of indicator evaluation further implies oil companies in the Niger Delta are more concerned about revenue from infrastructures operations and environmental consequences than the actual resistant capacities and interlinkages between the infrastructures. However, the application of this research approach in other industries and regions may show different outcome for interdependence and engineering capabilities depending on the prevailing climate situations and sensitivity of given infrastructure. This implies that the indicators developed for this study could be applied in other appropriate studies with expected variable results.

More so, the identification of critical infrastructure can take different approaches such as stakeholder voting and random selection (Bahadori, 2014). Though controversies and time required to agree on assets priorities often constraint these approaches, they provide a faster hands-on result for the practitioners to understand and adapt effectively to critical infrastructure protection. In this study, critical infrastructure priorities provide a common ground for more focused vulnerability assessment as stated in chapter one. Practitioners in the Niger Delta oil/gas industry could implement the outcome of this research by declaring emergency routine assets upgrade for the most critical infrastructure such as terminals, flow stations, roads, and bridges; for optimal operations. The rationale for criticality assessment in this study is also to pave the way for a focused vulnerability assessment in the next section according to the overall research aim. It also provides practitioners in the oil and gas industry who may adopt this research with a systematic pathway for selecting critical infrastructure for protection from climate change impact through a systematic process demonstrated in the framework.

8.7 Selection of vulnerable infrastructure

The concept of vulnerability was perceived by global powers as an approach to protecting critical infrastructures such as transport, telecommunication, and energy systems suspected to be targets of terrorists (Aradau, 2010). At the initial period, vulnerability assessment received extensive research focus and government patronage especially in the critical infrastructure sectors by both academics and experts (Moteff, 2005; Uhl, 2003). Little attention was given to vulnerability of critical infrastructure in terms of environmental impact until recently when climate change impact began to extend farther than estimated (Havko, Titko and Kováčová, 2017; Hemingway and Priestley, 2014; Intergovernmental Panel on Climate Change, 2014; Islam, Malak and Islam, 2013; McInnes et al., 2013; Balica, Wright and van der Meulen, 2012; Egan, 2007). These investigation's outcome and cited literature on climate vulnerability of coastal critical infrastructure address objective four and the fourth question of this study. It addresses the aim of this study, which was to conduct a vulnerability assessment of critical infrastructure in the Niger Delta.

This study revealed that vulnerability of critical oil/gas infrastructure in the Niger majorly due to exposure, proximity to climate risks areas, the presence of climate burdens, weak adaptive capacity, age and obsolescence of installations, interdependence, and criticality (sensitivity). This agrees with the findings of (Ouyang et al., 2009; S. Wang, Hong and Chen, 2012a; Adelekan, 2011; Tonmoy and El-Zein, 2013; Cabral et al., 2017; Brooks, Adger and Kelly, 2005; Jagtap and Bewoor, 2017).

From this study, 'Exposure' of critical infrastructure to climate-related risks is revealed as the most important indicator of vulnerability in the Niger Delta. This implies that at fabrication and installation stages of these systems, climate risks were not considered as crucial and catastrophic environmental consequences. The OML58 is a typical example, built without consideration for closeness to the Niger River or inundation potential. While critical infrastructures are exposed to climate risks, the focus of government is to ensure that all operating companies comply with the environmental impact assessment, monitoring and protection regulations. The Department of Petroleum Resources (DPR) and the National Oil Spill Detection and Response Agency (NOSDRA) focus on EIA reports as a criterion for licensing exploration and production in the region. This has exacerbated the severity of climate impact on critical infrastructure in recent years. This is because DPR and NOSDRA mandate companies to evaluate how their activities would impact on different environmental receptors and proposed mitigation measures with potential auditing and monitoring framework.

From the outcome of this study, it is imperative for the National government to institutionalise and operationalise Climate Impact Assessment (CIA) to embrace reporting, auditing, and monitoring in the oil and gas industry. The crucial reason for this urgency is that EIA does not seem to capture the intricacies involved in climate change impacts. While EIA dwells more on how exploration and production processes could impact on the environmental receptors (social, economic, environment – physical, chemical, and biological), CIA could focus on how the environment with a mix of climate change could affect the operational activities in the oil/gas industry. This is expected to be of utmost importance to the government because it holds a major share in most of the Joint Ventures in the Niger Delta, implying that the government stand a greater chance of losing investment if critical infrastructures are impacted. This implies that CIA would focus on screening, scoping, and prediction, impact mitigation, analysis and reporting, review and monitoring of prevailing climate change risk with the view to limit the severity of impacts of oil/gas activities and critical infrastructures. Operationalising CIA would imply the establishment of additional Climate Change Industrial Guidance and Regulations for the oil/gas industry in Nigeria. This could mandate the incorporation of adaptive mechanisms from the design stage of any sensitive infrastructure as it is the case with EIA.

8.8 The implication of adaptation strategies

This study uncovers some implementable adaptation strategies needed for resilience and resistance for vulnerable critical infrastructure against identified climate change burdens in the Niger Delta. Proposal for sustainable adaptation strategies addressed objective five and the fifth research question in chapter one of this study. Vulnerable infrastructure are systems expose to climate change impacts such as floods, storms surge, high temperature etc with little or no resistant capacity to cope with impact magnitude such that minor environmental change could trigger severe disruptions (Havko, Titko and Kováčová, 2017; Petzold and Ratter, 2015; Chai et al., 2011). However, a vulnerable critical infrastructure differs significantly from conventional vulnerable systems. A vulnerable critical infrastructure is therefore an asset of national priority (such as energy, telecom, and transport) without the capacity to cope with environmental disasters, such that when impacted could pose severe impact on the economic plans of State (Bloomfield et al., 2017; Kröger, 2008; Taylor, 2008; Egan, 2007). The ability of vulnerable infrastructure to resist the impact of environmental stress is known as adaptive capacity or resilience. This study focuses on evaluating critical oil and gas infrastructure for vulnerability. This implies that there are other vulnerable infrastructures in the industry and region that were discriminated based on criticality threshold. It further implies that suggested adaptation measures may not explicitly protect these from climate change impact.

By the principle of interdependence, non-critical systems are in the industry might be indirectly linked with prioritised systems where failure may negatively affect optimal operations of terminals, flow stations, pipelines, roads, transformers loading bays etc. However, with strategic implementation of suggested detailed adaptation measures emerging from this study such as the institutional adaptation approach (internal and external collaborations), excluded infrastructures are recognised in practice and protected.

Furthermore, some of the adaptation measures could be capital intensive such as groundwater and water discharge rate monitoring (flood alert systems) and require more scientific details for implementation. This seems to fail in meeting the “low or no regret” adaptation objective for sustainable practice (Heltberg, Siegel and Jorgensen, 2009; Cheong et al., 2013). Nevertheless, “no regret” adaptation is not judged based solely on the size of economic expenditure but also expected economic gains from implementing a costly adaptation option. Whereas, these options are developed to protect “critical” and highly prioritised infrastructures on which gross national earnings depends, yet if impacted could jeopardise the economic landscape of Nigeria. More so, low-cost options are designed to guide coastal and other planners on the best adaptation strategies that are realistic and meet the projected climate-related disasters (Cheong et al., 2013). This implies that practitioners could ensure that selected adaptation strategies are low cost and not regrettable without negating the maximum suitability of options for the given climate impact magnitude.

8.9 Adaptation and implication for PEAR strategy

From this study, experts and senior managers in the oil/gas industry claimed that they are concerned about how their operational and industrial risks could impact on people, environment, assets, and their reputation (PEAR) and how climate change could exacerbate the potential of disrupting their concern for maintaining high PEAR ethics. Since the aftermath of the 2012 flood, the moral landscape of most oil/gas organisations in meeting the set standards for PEAR has dropped significantly due to complicated environmental challenges (Idemudia, 2014). Management of these challenges in line with their impact on critical infrastructure, people in communities and personnel on board (POB), the environment, and reputation have been daunted. This was partly blamed on lack of vulnerability assessment tools, fussy understanding of prevailing climate change impact, and possible systems at risk.

This study has provided a framework, unveiled the prevailing climate change burdens, prioritised critical and vulnerable infrastructure and provided a scheme of adaptation measures to be adopted for building resistant and resilient infrastructure. Careful implementation of these measures will have significant improvement in strengthening actions and reactions expected to protect people, environment, critical assets, and reputation of the organisation. The physical adaptation through groundwater and water discharge rate monitoring could aid the organisations in planning for all elements included in the PEAR model. The substitution of cathodic pipes and with glass reinforcement epoxy (GRE) and duplex pipes reduce the risk of rust and continue to build confidence in the asset's element. Implementation of Unmanned Aerial Vehicles (UAVs) has the potential to draw prompt attention to reducing environmental impacts as well as providing timely data that reduce human exposure. Institutional collaborations and knowledge sharing provide an opportunity for more discussion and understanding of the subject matter while building corporate reputation across the industry.

Furthermore, implementation of adaptation measures is a strategic approach with the potential to boost investors' moral and confidence in investing in the oil/gas industry in line with the opinion of

(Kolk and Pinkse, 2004; Van den Hove, Le Menestrel and De Bettignies, 2002). Though adaptation has cost implications, it could potentially limit both uninsured and insured cost of insurance premiums paid on damaged critical infrastructure, eliminate the cost of litigation and fines and maintain organisation clean sheet (reputation) (Botzen and Van Den Bergh, Jeroen CJM, 2008; Linnerooth-Bayer and Mechler, 2006).

8.10 Emerging Issues

The next sections discuss emerging issues from the research, which were not captured in the research objectives but contribute significantly to the justification of the thesis findings and application of the research framework. It presents a case of conventional methodology failure and implementation of informal contact in navigating through gatekeepers in data collection. It also presents emerging cases of vulnerability and adaptation in practice as an outcome of observational fieldwork. The observational investigation was developed and integrated into the framework to widen the scope of data collection for vulnerability assessment and suitable triangulation of data collection and analysis approaches.

8.10.1 Informal research approach

Social research in the developed world is significantly different from the cultural understanding in the global south where political conflicts, cultural differences, and social crisis are predominant factors of life (Bulmer and Warwick, 1993). This research discovered an alternative approach to researching sensitive and highly ethically motivated organisations successfully through a crisis period in the Niger Delta context and how it may apply in other developing communities. Conducting a critical investigation on critical infrastructure in sensitive oil/gas organisations could have complicated the challenges as witnessed in this study but innovative investigation alternative was adapted to. It is being argued that frequent attacks on oil/gas installations such as pipelines in the region by militants (Anifowose et al., 2012) might have exacerbated the difficulties associated with accessing information on such installations for research purpose.

It was gathered that, conventionally, high profile recommendations from reputable organisations and thorough bureaucratic checks are instituted to recommend and approve the honest academic investigation. But during the crisis, access controls for all classes of visitors are temporarily blocked while security alert systems and threat levels raised (turned red). In this situation, negative impacts are posted on all time-bound academic investigations which depend on conventional social science methods and technical approaches as noted by (Edejer, 1999), initially adopted for this study.

In this study, initial conventional research approaches (accessing companies, the composition of focus groups and conduct of semi-structured interviews) failed in practice. However, the failure of the methods in practice was not due to poor design or lack of acknowledgement of institutional bureaucracies and ethics. To ensure these factors were properly captured for smooth fieldwork, an initial exploratory survey was conducted earlier in the research to underpin and study the requirements for successful fieldwork. It was found that the Niger Delta oil and gas research environment is transient, hence rigid research approaches have high tendencies of failure. In this study, major adjustments were made in line with prevailing realities to ensure the level of success established in the end. The adjustments adopted informal approaches – making informal contacts embracing gatekeepers, follow-up, and snowballing strategies; for effective and efficient data collection. Gatekeepers and contacts that were established informally are figures or institutions with the authority to grant researchers access to desired sample population or data. Most scholars devote little attention to gatekeepers despite their crucial role in social research as noted by (Crowhurst and Kennedy-macfoy, 2013). Findings suggest that making flexible research plans incorporating the gatekeeper through informal approaches is a realistic and fundamental strategy for researching successfully even during the crisis and social unrest in the Niger Delta.

8.10.2 TOTAL OML 58 and Chevron case

The impact of the 2012 flood on TE&PN OML 58 and Chevron producing operated marginal platforms demonstrate the effectiveness of installing critical infrastructure on elevated platforms as an adaptation strategy. Findings in this study suggest that the vulnerability of critical infrastructure is directly linked with inundation, which often exacerbates the severity of flood impacts. Elevation levels could be a sustainable best practice in the Niger Delta. Most critical infrastructure in coastal regions is vulnerable due to physical indicators that measure that distance from shoreline and elevation levels (Denner et al., 2015). Though this study falls short of detailed and close investigation of the Chevron platform, documentary evidence and interviews support the high elevated platform on which operations were continued throughout the flood. However, it was revealed that the Chevron platform is recently built with the suspicion that engineers could have raised the operational platform in acknowledgement of reoccurring flood events. This agrees with the proposed framework of this study, which seeks to identify developing infrastructure with the view to providing the inert resilience required to cope with environmental disasters forced by climate change (Udie, Bhattacharyya and Ozawa-Meida, 2018). It implies that terminals, flow stations, roads, wellheads, and power transformers could be installed in raised artificial platforms above the existing 4.5 meters above sea level to reduce the impact of the flood. This strategy agrees with the position of (Aradau, 2010; Atedhor, Odjugo and Uriri, 2011; Hallegatte, 2009).

Leveraging on the External Collaboration strategy for effective adaptation, TEPN and other companies and critical infrastructure owners in the Niger Delta could implement the Chevron mechanism for optimal operation during and after flood events. Raising the platforms above sea levels may not be limited to identify infrastructure in this study. Interdependence as a criterion in this study implies that there are other infrastructures that are indirectly linked to effective and efficient operations as argued by (Zimmerman, 2004b; Buldyrev et al., 2010). Hence, interlinked systems such as helipads, reservoirs, modular refineries etc. in the Niger Delta could be installed on high rising platforms for secured interdependence and maximum operations.

8.10.3 Flow Station Separator's case (Temperature Effect)

It is being contended that rise in global temperature could have a severe impact in different sectors of the economy such as energy, agriculture, and transport (Tingley and Huybers, 2013; Asseng et al., 2015; Gong, Guo and Ho, 2006). This study found a typical case that corroborates existing findings by the demonstration of the impact of increasing temperature on the optimal performance of separators and compressors in the flow stations. This case further fulfilled the achievement of objective one, which aims to review the potential impacts of climate change on critical oil/gas operations in the Niger Delta. However, this implies that temperature-dependent separators and compressors are vulnerable to climate change because the ambient temperature will continue to increase proportionally with the projected increase in global average temperature.

The oil and gas industries and all joint venture companies have the capacity to adopt a re-engineering process for critical infrastructure impacted by temperature to accommodate this change as suggested by (Klashner and Sabet, 2007). Impact of temperature on could reduce the operational efficiency and optimal performance of flow station leading to poor quality of crude products and market losses.

8.11 Chapter Summary

The discussion chapter presents the implications of major and minor research findings, how they fulfil the research objectives, major aim and address the set questions. Extensive reference to relevant literature is cited to support and justify the relevance of various outcome. Evidence of climate change (with a demonstrable impact on across the Niger Delta, including the aviation industry) was discussed. The implications of researching successfully in the Niger Delta utilising the principles of gatekeepers and informal contacts is presented as a more suitable approach for social investigation in the region. The emerging cases of evidence of vulnerability due to increase temperature forcing and adaptability due to high elevation installations are discussed as empirical lessons for assets managers. Importantly, the chapter discusses the achievement of research framework (scoping, vulnerability assessment and mainstreaming) as it was developed to drive the assessment to the conclusion, making it an effective tool for mainstreaming. Commercial implications of suggested adaptation strategies are discussed to enhance their understanding and the crucial need for implementation to ensure that organisational PEAR principle is maintained. The next chapter would drive the research towards its conclusion, with recommendations for further studies.

CHAPTER NINE
CONCLUSION AND RECOMMENDATIONS

9.1 Introduction

As stated at the beginning of this study (in Chapter 1), this thesis investigated the vulnerability of critical oil and gas infrastructure to climate change impacts in the context of the Niger Delta. The discussion chapter reflects generally on the outcome of the research findings. This chapter summarises the study achievements, main findings, contribution to knowledge and impact, emerging issues from the study, limitations and recommendations for further work.

9.2 Study outcome

In chapter one, the overview of the research is presented; through the lens of global warming, climate change, its impacts and consequences from a global perspective. It further presents the research background and pathway to the major aim, objectives and research questions. The background for the systematic review of literature is presented in chapter two which provided insight on the criteria selected for the vulnerability and criticality of climate change impact on infrastructure. The focus on vulnerabilities and impacts on coastal systems sets the justification for the choice of oil and gas infrastructure in this study as well as the rationale behind the focus on the Niger Delta as the study area.

The introduction, literature and framework chapters led to the achievement of objective one (1) Review of the potential impacts of climate change on oil/gas critical operations in the Niger Delta and objective (2) Design of a conceptual framework for the vulnerability assessment of critical oil and gas infrastructure in the Niger Delta. Accordingly, research question 1 and question 2 are addressed in chapters 2 and 3 respectively.

The operational mechanism of the study and how the research framework was demonstrated, is presented in Chapter four (Research Methods). It captures the study approaches, fieldwork designs and implementation. The research methodology explained the realistic process for the systematic fieldwork conducted for the study including data collection and analysis. It connects the existing literature and result/contribution to the body of knowledge. The chapter justifies the implementation of multi-criteria decision-making analysis tool (MCDA) – the analytical hierarchy process (AHP), as an effective tool for evaluating the criticality and vulnerability of oil/gas infrastructure in the study area.

This contributed to the achievement of objectives 3 and 4 of the study. The implementation of the research strategy for data collection and total reflection on fieldwork challenges and outcomes is presented in chapter 5. It describes the art of researching successfully in the Niger Delta using informal approaches.

Chapter six documented the implementation of the AHP in the quantitative analysis and evaluation of criticality and vulnerability of infrastructures in two separate sections. Section one evaluates the criticality of selected infrastructure leading to the achievement of objective 3 (to identify critical oil/gas infrastructure through a systematic pairwise comparison and prioritisation process) and addresses question 3. Section two further explained the vulnerability assessment of the critical infrastructures, contributing to the achievement of objective 4 (to evaluate the vulnerability of identified critical infrastructure to climate change impacts in the Niger Delta) and subsequently addressed research question 4.

Chapter seven evaluates and underpinned some distinct adaptation strategies suggested for the protection of vulnerable critical infrastructures from climate change impacts. The implication is the achievement of objective 5 (to suggest sustainable and practicable adaptation strategies for oil and gas infrastructure resilience in the Niger Delta) and addresses question 5.

9.3 Main findings

The assessment of critical oil and gas infrastructure for vulnerability to climate change impacts has revealed some outcomes that sum up to a hierarchical arrangement of selected systems.

The study ultimately found that the developed conceptual framework can be implemented and operationalised in the scoping and vulnerability assessment processes involving critical infrastructure. It demonstrates a systematic process of preliminary studies and exploratory investigation at the initial stages of the research and operates through an iterative process of assessment including re-scoping, stakeholders' selection, data collection and analysis. The rest of the findings signpost the mainstreaming of the entire framework mechanism in the oil and gas industry.

The main finding arising from this study is the identification of vulnerable systems and prioritisation of their criticality. This outcome presents to the industry the systems that are most vulnerable to a given indicator and the sensitive systems that require urgent attention during extreme climate events such as the flood in the Niger Delta. Adaptation planning and investment could depend on this outcome for effective and sustainable infrastructure management in the Niger Delta.

The study also found that Multi-criteria Decision-making Analysis (MCDA) tool - analytic hierarchy process (AHP), can be effectively applied in the assessment of critical infrastructure vulnerability to climate change impacts. Its application in the global south context and in the Niger Delta oil and gas industry is highly relevant.

Furthermore, sustainable adaptation strategies and responses have been analysed and presented. Implementation of suggested adaptation options could reduce systems susceptibility and build the resilience and resistance required to cope with extreme climate events.

The study found evidence of climate change impacts in the Niger Delta oil and gas industry with limited maximum coping abilities, from both the adaptive capacities of built systems and institutional capacity. The burdens of climate change exacerbating environmental challenges in the industry include frequent flood events, rising regional temperature, rising sea level and surging Atlantic tide, frequent storms and heavy rainfall accompanied by a lightning discharge. The study found that an increase in temperature directly disrupts the operation of compressors at the flow stations, reducing crude oil production, which could potentially affect economic stability of the industry.

In addition, infrastructures built on elevated platforms are less likely to be impacted by floods, rising sea levels and tidal surges compared to those on inundated platforms. Hence, vulnerability to the prevailing flood depends majorly on the elevation of the systems and the magnitude of a flood event. The vulnerability of one system could cascade directly or indirectly to linked systems in the value chain.

In terms of methodology, the study found that conventional social science research strategies proposed by (Bryman, 2016; Krueger and Casey, 2009; Johnson and Onwuegbuzie, 2004; Harvey, 2010) may not apply in the Niger Delta oil and gas industry. This study thus provides an alternative informal research strategy for researching successfully in the Niger Delta. The strategy incorporates gatekeeper, external contacts and snowballing as links for data collection opposed to conventional approaches.

Nevertheless, this study has demonstrated a consistent and systematic approach that experts and practitioners in the oil and gas industry can adopt for the assessment of critical infrastructure vulnerability to climate change and other disasters' impacts. Importantly, the approach is flexible and adaptable for investigating systems in renewable energy, hydropower, engineering, mining and other industries such as transport, telecommunication, agriculture, tourism, etc. It has provoked scholarly activities (teaching and research) in climate change impacts in relation to the oil and gas industry and natural resources management in the Niger Delta.

9.4 Contributions and Impacts

Study findings enabled the following fundamental contributions to knowledge in the industry, policy research, teaching and update of professional development (CPD) for personnel.

9.4.1 Industrial contribution

The conceptual framework for vulnerability assessment of critical oil and gas infrastructure to climate change is an empirical tool that is implementable inbuilt systems assessment beyond the Niger Delta. Its flexibility and adaptability can be leveraged across industries – transport, telecommunication, IT, Energy, etc. for assessment. The list of critical and vulnerable infrastructure formed a new database for assets managers in the industry to adopt for adaptation analysis, planning and investment. The study also contributed towards implementation of Analytic Hierarchy Process (AHP) for the investigation of the criticality and vulnerability of oil and gas industry through stakeholder participation. It can be implemented through an interdisciplinary multi-stakeholder approach in industrial decision-making issues, eliminating voting and usual conflicts associated with multiple choice decision activities while strengthening multiple choice decision-making process in the industry.

9.4.2 Policy Contribution

The overall contribution of this study in terms of policy is for the development and update of policies on Environmental Guidelines and Standards for Petroleum Industries in Nigeria (EGASPIN). Some of these include Oil Pipeline Ordinance (1956), Petroleum Refining Regulations (1974) and The Mineral Oils (safety) Regulation (1963), and National Petroleum Policy. It also contributes an eye-opening framework that could initiate the development of a Critical Infrastructure Protection and Regulation Policy aimed at protecting sensitive infrastructure from the impacts of climate change. Policy makers in infrastructure management in Nigeria and other concerned regions could also leverage this study to develop internal policy mechanisms for critical systems protection as a means of protecting contamination of ground and surface water, air pollution, forest reserves and wildlife. The study also contributed to a new proposition for EIA arguing for the inclusion of climate impact assessment (CIA) into conventional EIA processes as a policy in the Nigeria oil and gas industry. This is because, while EIA focuses on how oil/gas operations could impact on the environment, CIA focuses on how the environment could impact on oil/gas industrial operations, taking into consideration prevailing climate projections.

9.4.3 Academic contribution – Research

At the beginning of this study, it was established that limited scholarly literature exists in the subject area. The study has opened a new frontier for further climate and environmental research in the Niger Delta. The framework, methodologies and adaptation strategies are potential and relevant tools for further academic work within the industry. They also offer multiple investigation opportunities to further support the outcomes of this study while extending the possibilities of implementing sustainable solutions to the challenges of climate change, through scholarly research. The study recommendations are crucial contributions that signpost other researchers to future areas of investigations in the oil and gas industry globally.

9.4.4 Academic contribution – Teaching

The applied systematic literature review pathway, application of informal approaches in field studies, pairwise comparison and analysis using the AHP in prioritising critical and vulnerable infrastructure; are relevant tools for the teaching of research methods. The study of climate change and its impact on oil and gas is relatively new in the Niger Delta context. This study provides a new debate for the inclusion of climate change studies in the academic curriculum of Nigerian Universities, importantly in the Niger Delta, to ensure that deeper adaptation awareness is created across the region.

Nonetheless, in addition to the contributions and impacts described above, this study could have other various impacts, directly or indirectly on oil and gas companies or the industry. The research framework has the potential to influence industrial, government and inter-agency policy direction on critical oil/gas infrastructure protection, climate change adaptation planning and investment analysis. Though the investigation focuses on the Niger Delta, criticality and vulnerability data and adaptation recommendations could be used for regional sustainability and management of critical assets when faced with climate change impacts and vulnerabilities. Similarly, oil and gas companies operating in North-Eastern Europe, North and South America, Gulf states oil and gas industries and African National companies such as Algeria, Angola, Egypt, Ghana, and Libya; could also mainstream the framework and methodology for policy development and prioritise their systems for protection from climate impacts. More specifically, the successful application of AHP indicates that it could make a significant impact if applied across the oil and gas infrastructure value chain (upstream, midstream and downstream sectors).

9.5 Emerging Issues

Some critical issues emerged from the study due to empirical exploratory investigation and the implementation of theoretical design. These are discussed below:

- ✓ Chapter five documents a critical reflection on the emerging challenges associated with recruitment of research participants and data collection in the Niger Delta underpinning the dependence on **informal contacts** approaches as optional procedures for researching in the study area. It is presented as a guideline for intending researchers in the Niger Delta and as an update of theories of empirical social research focusing in related regions to note.
- ✓ Secondly, the emerging disruptions perpetuated by rising ambient temperature because of regional temperature rise and consequential impacts on the operations of Flow Stations is documented. This validates the vulnerability of sensitive systems and contributed to the achievement of objective 1 of this study.
- ✓ Graphical evidence from the 2012 flood also presents crucial issues that centred on vulnerability due to inundation. It presents the case of less impacted Chevron operational platform due to its high elevation as opposed to the TOTAL OML 58 which was adversely impacted due to low elevation.

9.6 Limitations of the Study

This research was designed based on some boundaries for an in-depth investigation of vulnerability in the context of the Niger Delta. In every piece of research, there are limitations because of focus and specific aims and objectives. Considering this, some limitations to this study include that the investigation focuses on the oil and gas industry in the Niger Delta, hence argues on issues from the perspective of the region. Due to the study structure and focus, a social and economic aspect of sustainability of communities, economic systems, tourism and the impacts on corporate social responsibility are not included. Adaptation strategies are analysed and presented with the expectations that further cost and benefits analysis could aid assets managers in the understanding of adaptation economics. The study adapted and effectively operationalised AHP and could not consider implementing other MCDA models such as the Analytic Network Process (ANP). Notably, the study deliberately focuses on climate adaptation to argue that critical systems require both resilience and resistance against climate change to function effectively. Therefore, mitigation element of climate change is peripherally discussed in this study.

9.7 Recommendations for Future Work

The research could not provide a holistic solution to the challenges of climate change in the Niger Delta; from both expert and academic perspectives as previously described. Therefore, the following areas could be further investigated:

- Detailed investigation with a focus on conducting a cost-benefit analysis of selected adaptation options to provide various options for a no-regret adaptation investment.
- A comparative climate impact and vulnerability assessment of critical oil and gas infrastructure in Ghana and Nigeria could be attempted with the view to underpinning specific areas of knowledge sharing and collaborative adaptation investments.
- The research framework and methodology could be further applied in the assessment of other critical coastal infrastructure such as residential, renewable energy, transport and telecommunication at both national, regional and international levels.
- The methodology could be further applied in prioritising mitigation options through interdisciplinary and multi-stakeholder approach involving the industry, communities, and local government and policymakers; to develop a robust mitigation approach in the Niger Delta and beyond.

In conclusion, the study has achieved all of its main aims, objectives and addresses the research questions outlined in chapter one; it illuminates the vulnerability of the Niger Delta to climate change impacts, achieved the design of a conceptual framework for vulnerability assessment, prioritisation of critical infrastructure, evaluation of vulnerable critical infrastructure, and recommendation of specific adaptations strategies to be implemented for critical infrastructure protection. With these achievements and the proposed adaptation measures, in theory, the study argued that researchers, practitioners, policymakers, oil companies and all stakeholders in the Niger Delta oil and gas industry will consider these outcomes and operationalise (mainstream) the recommendations across the infrastructure value chain as described in the framework. The practical implementation of the research framework and its outcomes will significantly increase the sustainability, resilience and resistance of vulnerable critical oil/gas infrastructures to climate change impacts in the Niger Delta.

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APPENDICES

Appendix I Consent form

STUDY TITLE: VULNERABILITY ASSESSMENT OF CLIMATE CHANGE IMPACT ON OIL AND GAS INFRASTRUCTURE IN THE NIGER DELTA.

Issue	**Respondent's initial**
I have read the information presented in the information sheet about the study "Vulnerability Assessment of Climate Change Impact on Oil and Gas Infrastructure in the Niger Delta."	
I have had the opportunity to ask any questions related to this study, and received satisfactory answers to my questions, and any additional details wanted.	
I am also aware that excerpts from the interview may be included in publications to come from this research. Quotations will be kept anonymous.	
I give permission for the focus group discussion to be recorded using audio recording equipment.	
I understand that relevant sections of the data collected during the study would be analysed for academic purposes in De Montfort University leading to the publication of results.	

With full knowledge of all foregoing, I agree to participate in this study.
I agree to be contacted again by the researcher if my responses give rise to interesting findings or cross references.

☐ No
☐ Yes

If yes, my preferred method of being contacted is:
☐ Telephone …………………………………………………..
☐ Email …………………………………………………………..
☐ Other …………………………………………………………..

Participant Name:		Consent taken by	
Participant Signature:		Signature	
Date		Date	

Appendix II Participant's Information Sheet

STUDY TITLE: VULNERABILITY ASSESSMENT OF CLIMATE CHANGE IMPACT ON OIL AND GAS INFRASTRUCTURE IN THE NIGER DELTA

Dear Participant,

My name is Justin Udie and I am a doctorial researcher at the De Montfort University, The Gateway, Leicester, LE1 9BH UK; pursuing studies leading to a PHD in Climate Change Impact Assessment. My research focus is on the **"Vulnerability Assessment of climate change impact on oil and gas infrastructure in the Niger Delta",** for which I am sponsored by Petroleum Technology Development Fund (PTDF) Nigeria.

This research aims to achieve the following objectives:

i. To identify the risks and vulnerability of oil/gas infrastructure to climate change in the Niger Delta.
ii. To design a systematic approach for vulnerability assessment of climate change impact on oil and gas infrastructure in the Niger Delta.
iii. To critically assess the vulnerability of oil/gas infrastructure (pipelines) to climate risks.
iv. To identify, evaluate and suggest adaptation and mitigation measures (for new and existing infrastructures) against climate risks.
v. To estimate the operating cost of mitigation and adaptation measures compared with a *"business as usual"* approach.

To achieve these objectives, I am collecting primary data through interactions with relevant stakeholders, mainly through focus groups. I would like you to participate in this study and support me in achieving my research objectives.

The focus group discussion is expected to last between 60 to 90 minutes. This study may also demand for documentary and audio records (as evidence and reference materials). The information you provide is confidential. Your name or any other personal identifying information will not appear in any publications resulting from this study; neither will there be anything to identify your place of work. The information gained from this focus group will only be used for the above objectives, will not be used for any other purpose and will not be recorded in excess of what is required for the research.

Participation in this study is voluntary. You may decide to withdraw at any stage of the process. If you notify us of your withdrawal, all identifiable data will be destroyed except where there is an obvious impossible reason to isolate individual contribution after data has been anonymised. I may contact you again asking for clarification of issues raised in the discussion sometime after it has taken place, you will not be obliged in any way to clarify or participate further.

Though the study findings will be published in international conferences and journals, only the research team will have access to the interview data itself. There are no known or anticipated risks to you as a participant in this study.

If you have any questions regarding this study or would like additional information please ask the researcher before, during, or after the interview.
Please find below the contact information of my supervisor so that he can be contacted regarding displeasure or disagreement on any aspect of the research process:

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Yours Sincerely,

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Appendix III Definition of Terms Participants

1. **Environmental Concerns:** is the measures of impacts caused by climate burdens resulting in multiple negative effects on human lives, biodiversity, air quality, fresh and groundwater, property and the entire ecological system.
2. **Impact on Human Health and Safety:** is the measure of various impacts on human health and safety because of the failure of infrastructures due to climate change burdens.
3. **Impact on the ecosystem:** the continual severe impact on the ocean, coastal and terrestrial ecosystem leading to the death of animals, phytoplankton, seabirds, fish, corals and the entire aquatic food chain and food web due to climate impact on infrastructures.
4. **Availability of Alternative:** is the consideration of possible alternative systems to support infrastructure in case of any climate impact situation.
5. **Cost of Alternatives:** is the cost or economic value of alternative systems or substitutes for an infrastructure that is being or has been negatively impacted by climate change burdens.
6. **Economic Niche:** this is the financial gains expected from infrastructure investment in the economy.
7. **Societal Relevance:** Societal relevance is the measures of secondary impacts on other businesses and aesthetics such as hospitality and tourism, commercial, educational, social infrastructures etc. that depends significantly on impacted oil/gas infrastructure.
8. **Replacement Cost:** is the estimated expenditure on replacing the exact infrastructure that is in place and being impacted by climate change-induced risks.
9. **CRITICALITY** is the measure of the impact level on the society as a result of failure or loss of an asset OR the "contribution level of the infrastructure to the society" in sustaining a minimum standard and quality of life.
10. **PRESENCE OF CLIMATE BURDENS**: refers to the probability that climate risk(s) abounds around an infrastructure in a given geographical area (UNEP 2008).
11. **EXPOSURE:** an infrastructure describes how open or the level of "unprotectedness" of an infrastructure is to climate burdens/risks.
12. **PROXIMITY:** is the estimated distance (the closeness) of an infrastructure to possible climate risks or vulnerable zones.
13. **ADAPTIVE CAPACITY** is the sustainable ability (technological or managerial concepts) of an infrastructure to withstand or adjust to accommodate climate change burdens.

14. **AGE** of an infrastructure is an appraisal of its lifespan and performance from the date of installation to present point of assessment.
15. **INTERDEPENDENCE;** is the interconnectivity and dependencies of infrastructures such as electrical, water, telecommunication, roads, oil/gas, tourism systems etc. on each.
16. **CLIMATE VULNERABILITY** is "the degree to which a system is susceptible to or unable to cope with, adverse effects of climate change, such as extreme temperatures, flooding, storms and heavy downpour" (Patwardhan et al., 2007; Adelekan, 2011a).

Appendix IV Semi-structured Elite Interview Questionnaire

Introduction: Global climate is changing, and projections suggest that sea level and temperature will increase proportionally up to 1.9 m and at least 2.0°C respectively by the end of 2100. This implies that there would be more storms, high tides, heavy downpours, more heat and frequent flood actions; Fragile ecosystems such as coastal areas and deltas are argued to be at risks of these impacts; where the Niger Delta research becomes crucial due to critical oil/gas infrastructures (of high economic interest). Adaptation and mitigation could protect critical oil and gas infrastructures from disruptions and failure.

This questionnaire is a research tool for the assessment of vulnerability of critical oil/gas infrastructures to climate change impact in the Niger delta. The data would be analysed with other documentary evidence to illuminate the susceptibility of critical oil/gas infrastructures to climate risks/burdens in the Niger Delta Context.

Confidentiality: Before commencing the interviews, please ensure that you read the participants' information sheet and sign the attached confidentiality form. Once again the data from this interview will only be used for research purposes and will not be disclosed to a third partybased on Data Protection Act.

The questions are based on specific themes on;

1. **Presence of Burden(s)**

What are the prevailing climate risks in the Niger Delta? *Give examples*

Are there incidences of climate change in the region? How frequent?

Would you agree that oil/gas infrastructures are vulnerable these risks?

2. **Exposure**

Are your infrastructures buried or laid open on the earth surface?

Do you think buried or surface laid assets could be at risk of climate impacts? *Why?*

Has any of these infrastructures been affected or overrun by tides, floods, storms; leading to an emergency shutdown?

3. **Criticality**

Which do you consider are the most critical infrastructures in the oil/gas value chain of your organisation? *(Accept some named assets a, b, c,..n)*

Why are these considered most critical? *Base on any possible criteria?*

What could be the effects of losing these assets due to high tides, flood and or storms?

4. **Proximity/Location**

Within your assets portfolio, are there oil/gas infrastructures located on Islands, areas prone to inundation, sea shores and river banks; that you think could be severely impacted by high tides, floods or storms? Examples and why?

How close (distance in KM) are these assets to high-risk areas? *(E.gs, and Seek to get records of elevations of named critical infrastructures)*

Do you think the distance between these infrastructures and the sea shores, river banks, storm corridors is a threat? Please explain?

5. **Adaptive Capacity**

Are there possible invested adaptation mechanism (such as dual fittings, coating, jack-ups, etc) sustaining your infrastructures? *(Consider examples mentioned in 2 above one after the other)*

What is your organisations' regarding adaptation investment?

Do government's policies support climate change adaptation in this sector?

6. **Aging Infrastructure and life cycle**

Do you think the age of an infrastructure could determine the level of vulnerability?

What is the present average age of your critical infrastructures *(3 above)*?

Do you expect that climate change may cause sudden replacement or premature decommissioning anytime soon? *(Look up for a table containing assets and year of installations)*

7. **Interdependent Infrastructure**

Are oil/gas infrastructures interlinked such that impact on one can cause effects on the other?

Do you think it is possible to detached infrastructures from possible vulnerable networks?

How costly are they to be replaced?

8. **Time**

Are these infrastructures periodically assessed for climate risks? If yes, how often? *(Appeal for log books/reports of assessments)*

Do you think that oil/gas infrastructures could be more vulnerable with time (say 2030, 2050, 2080 and 2100)

Thank you for your time and contributions

Appendix V Criticality Assessment Questionnaire

Introduction to Assessment Process

As the global climate continues to change, threats on coastal and delta regions of the world continue to amass. Oil and gas infrastructures located in these risk-prone areas such as deltas and coastal areas; could be at risk of **flooding (due to sea level rise), rising tides, storms, and extreme temperature.** To assess how the Niger Delta oil/gas infrastructures could be vulnerable to these climate burdens, I chose to present some critical assets which you will be required to rank based on how they may appear CRITICAL to you and your organisation.
However, this process is divided into two sections. The GOAL of the first is to prioritise and rank oil/gas infrastructures based on their CRITICALITY in the Niger Delta. The criteria, sub-criteria for ranking and the infrastructures are given in the table below:

<table>
<tr><th>Criteria and sub-criteria</th><th>Infrastructures</th></tr>
<tr><td>1. Interdependence or interconnectivity
2. Economic Niche
    i. Replacement cost
    ii. Economic/societal relevance
3. Environmental concerns
    i. Impact on Health/Safety
    ii. Impact on Ecosystem
4. Design complexity
    i. Availability of Alternative(s)
    ii. Cost of Alternative(s)</td><td>i. Oil and gas terminals
ii. Pipelines (Trunk lines (12 – 30”) and Flow line or bulk lines (6 – 8 “)
iii. Flow stations
iv. Oil well
v. Loading Bays
vi. Transformers and High voltage cables
vii. Roads and Bridges</td></tr>
</table>

Instructions: Section one has four (4) steps; step 1 and 2 are for the pairwise comparisons of main criteria and sub-criteria, step 3 is the combined comparison of criteria and sub-criteria while step 4 is the comparison of the criteria with the alternatives (infrastructures).
Process: Using the Saaty numerical scale (1 – 9 shown in the table below), pairwise compare two elements (**A** and **B**) DEPENDING ON HOW IMPORTANT you consider them in terms of CRITICALITY OF INFRASTRUCTURE.

Numerical Scale	Verbal scale
1	Equal importance (A = B)
3	Moderate important (A is slightly important than B)
5	Strongly important (A is strongly important than B)
7	Very strongly important (A very strongly important than B)
9	Extreme important (A is extremely important than B)
2,4,6,8	Intermediate values

Example, if you think criterion **“A”** is **VERY STRONGLY IMPORTANT** compared to criterion **“B**” with respect to **CRITICALITY OF INFRASTRUCTURES**, then tick the box under **“A”** and box **“7” to the right.** But if **“B”** is **VERY STRONGLY IMPORTANT** compared to A, then tick box **“7”** to the right of the scale.

NOTE: CRITICALITY is the **measure of the impact level matted on the society as a result of failure** or loss of capacity of an asset and or the **“contribution level of the infrastructure to the society”** in sustaining a minimum standard and quality of life through economic, safety, health, and security (Theoharidou, Kotzanikolaou and Gritzalis, 2010b; Fekete, 2011a)

STEP 1: Between the criteria under "A" and "B", choose which is important and tick the box under it and using the scale '1 – 9' decide **HOW MUCH IMPORTANT** you consider it with particular respect to the – **CRITICALITY OF OIL/GAS INFRASTRUCTURES** in the Niger Delta.

CRITERION A	CRITERION B	EQUALLY IMPORTANT	MODERATELY IMPORTANT	STRONGLY IMPORTANT	VERY STRONGLY IMPORTANT	EXTREMELY IMPORTANT
Interdependence ☐	Economic Niche ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Interdependence ☐	Environmental ☐ Concerns	☐ 1	3 ☐	5 ☐	☐ 7	9 ☐
Interdependence ☐	Engineering ☐ Capacity	☐ 1	☐ 3	5 ☐	☐ 7	9 ☐
Economic ☐ Niche	Environmental ☐ Concerns	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Economic Niche ☐	Engineering ☐ Capacity	1 ☐	3 ☐	☐ 5	☐ 7	☐ 9
Environmental ☐ Concerns	Engineering ☐ Capacity	1 ☐	3 ☐	☐ 5	☐ 7	9 ☐

STEP 2: ***Please pairwise compare the sub-criteria individually with respect to the nodal criteria indicated in bold***

CRITERION A	CRITERION B	EQUALLY IMPORTANT	MODERATELY IMPORTANT	STRONGLY IMPORTANT	VERY STRONGLY IMPORTANT	EXTREMELY IMPORTANT
Economic Niche						
Replacement cost	Societal Relevance	1	3	5	7	9
Environmental Concerns						
Impact on Health/Safety	Impact on Ecosystem	1	**3**	**5**	**7**	**9**
Engineering Capacity						
Availability of Alternative(s)	Cost of Alternative(s)	1	**3**	**5**	7	9

STEP 3: Please pairwise compare all the criteria jointly to decide the most **CRITICAL** oil/gas infrastructures in the Niger Delta by determining their weights

CRITERION A	CRITERION B	EQUALLY IMPORTANT	MODERATELY IMPORTANT	STRONGLY IMPORTANT	VERY STRONGLY IMPORTANT	EXTREMELY IMPORTANT
Interdependence	Replacement cost	1	3	5	7	9
Interdependence	societal relevance	1	3	5	7	9
Interdependence	Impact on Health/Safety	1	3	5	7	9
Interdependence	Impact on Ecosystem	1	3	5	7	9

Interdependence	Availability of Alternative(s)	1	3	5	7	9
Interdependence	Cost of Alternative(s)	1	3	5	7	9
Replacement cost	societal relevance	1	3	5	7	9
Replacement cost	Impact on Health/Safety	1	3	5	7	9
Replacement cost	Impact on Ecosystem	1	3	5	7	9
Replacement cost	Availability of Alternative(s)	1	3	5	7	9
Replacement cost	Cost of Alternative(s)	1	3	5	7	9
societal relevance	Impact on Health/Safety	1	3	5	7	9
societal relevance	Impact on Ecosystem	1	3	5	7	9
societal relevance	Availability of	1	3	5	7	9

	Alternative(s)					
Societal relevance	Cost of Alternative(s)	1	3	5	7	9
Impact on Health/Safety	Impact on Ecosystem	1	3	5	7	9
Impact on Health/Safety	Availability of Alternative(s)	1	3	5	7	9
Impact on Health/Safety	Cost of Alternative(s)	1	3	5	7	9

STEP 4*; the next comparisons would allow you to compare all the infrastructures taking one criterion at a time. The criterion to be compared is written in* ***red***

CRITERIA A	CRITERIA B	EQUALLY IMPORTANT	MODERATELY IMPORTANT	STRONGLY IMPORTANT	VERY STRONGLY IMPORTANT	EXTREMELY IMPORTANT
1. INTERDEPENDENCE						
Terminals	Pipelines	1	3	5	7	9
Terminals	Flow stations	1	3	5	7	9
Terminals	Oil well	1	3	5	7	9
Terminals	Loading Bay	1	3	5	7	9
Terminals	Transformers/HVC	1	3	5	7	9

Terminals	Roads & Bridges	1	3	5	7	9
Pipelines	Flow stations	1	3	5	7	9
Pipelines	Oil well	1	3	5	7	9
Pipelines	Loading Bays	1	3	5	7	9
Pipelines	Transformers/HVC	1	3	5	7	9
Pipelines	Roads & Bridges	1	3	5	7	9
Flow stations	Oil well	1	3	5	7	9
Flow stations	Loading Bays	1	3	5	7	9
Flow stations	Transformers/HVC	1	3	5	7	9
Flow stations	Roads & Bridges	1	3	5	7	9
Oil well	Loading Bays	1	3	5	7	9
Oil well	Transformers/HVC	1	3	5	7	9

Oil well	Roads & Bridges	1	3	5	7	9
Loading Bays	Transformers/HVC	1	3	5	7	9
Loading Bays	Roads & Bridges	1	3	5	7	9
Transformers/HVC	Roads & Bridges	1	3	5	7	9

CRITERION A	CRITERION B	EQUALLY IMPORTANT	MODERATELY IMPORTANT	STRONGLY IMPORTANT	VERY STRONGLY IMPORTANT	EXTREMELY IMPORTANT
2. REPLACEMENT COST						
Terminals	Pipelines	1	3	5	7	9
Terminals	Flow stations	1	3	5	7	9
Terminals	Oil well	1	3	5	7	9
Terminals	Loading Bays	1	3	5	7	9
Terminals	Transformers/HVC	1	3	5	7	9
Terminals	Roads & Bridges	1	3	5	7	9
Pipelines	Flow stations	1	3	5	7	9

Pipelines	Oil well	1	3	5	7	9
Pipelines	Loading Bays	1	3	5	7	9
Pipelines	Transformers/HVC	1	3	5	7	9
Pipelines	Roads& Bridges	1	3	5	7	9
Flow stations	Oil well	1	3	5	7	9
Flow stations	Loading Bays	1	3	5	7	9
Flow stations	Transformers/HVC	1	3	5	7	9
Flow stations	Roads & Bridges	1	3	5	7	9
Oil well	Loading Bays	1	3	5	7	9
Oil well	Transformers/ HVC	1	3	5	7	9
Oil well	Roads & Bridges	1	3	5	7	9
Loading Bays	Transformers/HVC	1	3	5	7	9

Loading Bays	Roads & Bridges	1	3	5	7	9
Transformers/HVC	Roads & Bridges	1	3	5	7	9
3. **SOCIETAL RELEVANCE**						
Terminals	Pipelines	1	3	5	7	9
Terminals	Flow stations	1	3	5	7	9
Terminals	Oil well	1	3	5	7	9
Terminals	Loading Bays	1	3	5	7	9
Terminals	Transformers/HVC	1	3	5	7	9
Terminals	Roads & Bridges	1	3	5	7	9
Pipelines	Flow stations	1	3	5	7	9
Pipelines	Oil-Well	1	3	5	7	9
Pipelines	Loading Bays	1	3	5	7	9
Pipelines	Transformers/HVC	1	3	5	7	9

Pipelines	Roads & Bridges	1	3	5	7	9
Flow stations	Oil well	1	3	5	7	9
Flow stations	Loading Bays	1	3	5	7	9
Flow stations	Transformers/HVC	1	3	5	7	9
Flow stations	Roads & Bridges	1	3	5	7	9
Oil well	Loading Bays	1	3	5	7	9
Oil well	Transformers/HVC	1	3	5	7	9
Oil well	Roads & Bridges	1	3	5	7	9
Loading Bays	Transformers/HVC	1	3	5	7	9
Loading Bays	Roads & Bridges	1	3	5	7	9
Transformers/HVC	Roads & Bridges	1	3	5	7	9
4. IMPACT ON HEALTH AND SAFETY						
Terminals	Pipelines	1	3	5	7	9

Terminals ☐	Flow stations ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Terminals ☐	Oil well ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Terminals ☐	Loading Bays ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Terminals ☐	Transformers/ ☐ HVC	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Terminals ☐	Roads & Bridges ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Pipelines ☐	Flow stations ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Pipelines ☐	Oil well ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Pipelines ☐	Loading Bays ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Pipelines ☐	Transformers/ HVC ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Pipelines ☐	Roads & Bridges ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Flow stations ☐	Oil well ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Flow stations ☐	Loading Bays ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9

Flow stations	Transformers/HVC	1	3	5	7	9
Flow stations	Roads & Bridges	1	3	5	7	9
Oil well	Loading Bays	1	3	5	7	9
Oil well	Transformers/HVC	1	3	5	7	9
Oil well	Roads & Bridges	1	3	5	7	9
Loading Bays	Transformers/ HVC	1	3	5	7	9
Loading Bays	Roads & Bridges	1	3	5	7	9
Transformers/HVC	Roads & Bridges	1	3	5	7	9
5. IMPACT ON ECOSYSTEM						
Terminals	Pipelines	1	3	5	7	9
Terminals	Flow stations	1	3	5	7	9
Terminals	Oil well	1	3	5	7	9
Terminals	Loading Bays	1	3	5	7	9

Terminals	Transformers/HVC	1	3	5	7	9
Terminals	Roads & Bridges	1	3	5	7	9
Pipelines	Flow stations	1	3	5	7	9
Pipelines	Oil well	1	3	5	7	9
Pipelines	Loading Bays	1	3	5	7	9
Pipelines	Transformers/HVC	1	3	5	7	9
Pipelines	Roads & Bridges	1	3	5	7	9
Flow stations	Oil well	1	3	5	7	9
Flow stations	Loading Bays	1	3	5	7	9
Flow stations	Transformers/HVC	1	3	5	7	9
Flow stations	Roads & Bridges	1	3	5	7	9
Oil well	Loading Bays	1	3	5	7	9

Oil well	Transformers/HVC	1	3	5	7	9
Oil well	Roads & Bridges	1	3	5	7	9
Loading Bays	Transformers/HVC	1	3	5	7	9
Loading Bays	Roads & Bridges	1	3	5	7	9
Transformers/HVC	Roads & Bridges	1	3	5	7	9
6. AVAILABILITY OF ALTERNATIVE(S)						
Terminals	Pipelines	1	3	5	7	9
Terminals	Flow stations	1	3	5	7	9
Terminals	Oil well	1	3	5	7	9
Terminals	Loading Bays	1	3	5	7	9
Terminals	Transformers/HVC	1	3	5	7	9
Terminals	Roads & Bridges	1	3	5	7	9
Pipelines	Flow stations	1	3	5	7	9

Pipelines	Oil well	1	3	5	7	9
Pipelines	Loading Bays	1	3	5	7	9
Pipelines	Transformers/HVC	1	3	5	7	9
Pipelines	Roads & Bridges	1	3	5	7	9
Flow stations	Oil well	1	3	5	7	9
Flow stations	Loading Bays	1	3	5	7	9
Flow stations	Transformers/HVC	1	3	5	7	9
Flow stations	Roads & Bridges	1	3	5	7	9
Oil well	Loading Bays	1	3	5	7	9
Oil well	Transformers/HVC	1	3	5	7	9
Oil well	Roads & Bridges	1	3	5	7	9
Loading Bays	Transformers/HVC	1	3	5	7	9

Loading Bays	Roads & Bridges	1	3	5	7	9
Transformers/HVC	Roads & Bridges	1	3	5	7	9

7. COST OF ALTERNATIVES

Terminals	Pipelines	1	3	5	7	9
Terminals	Flow stations	1	3	5	7	9
Terminals	Oil well	1	3	5	7	9
Terminals	Loading Bays	1	3	5	7	9
Terminals	Transformers/HVC	1	3	5	7	9
Terminals	Roads & Bridges	1	3	5	7	9
Pipelines	Flow stations	1	3	5	7	9
Pipelines	Oil well	1	3	5	7	9
Pipelines	Loading Bays	1	3	5	7	9
Pipelines	Transformers/HVC	1	3	5	7	9

Pipelines	Roads & Bridges	1	3	5	7	9
Flow stations	Oil well	1	3	5	7	9
Flow stations	Loading Bays	1	3	5	7	9
Flow stations	Transformers/HVC	1	3	5	7	9
Flow stations	Roads & Bridges	1	3	5	7	9
Oil well	Loading Bays	1	3	5	7	9
Oil well	Transformers/HVC	1	3	5	7	9
Oil well	Roads & Bridges	1	3	5	7	9
Loading Bays	Transformers/HVC	1	3	5	7	9
Loading Bays	Roads & Bridges	1	3	5	7	9
Transformers/HVC	Roads & Bridges	1	3	5	7	9

PLEASE THANK YOU SO MUCH FOR YOUR TIME, GOD BLESS

Appendix VI Vulnerability Assessment Questionnaire

Goal: Assessing the Vulnerability of oil/gas Infrastructures
Instructions: this section has two steps**. In Step 1,** please pairwise compare the **CRITERIA** with each other to determine their global importance (WEIGHT) with respect to the **GOAL**. The criteria and infrastructures are given in the table below:

Criteria	Infrastructures
1. **Adaptive capacity** of infrastructure **2. Age of the infrastructure** 3. **Interdependence** or linkage with other infrastructures 4. **Presence of climate burdens or risk** around the infrastructure 5. **Exposure** of the infrastructure to climate risks 6. **Criticality** of the infrastructure 7. **The proximity** of the infrastructure to climate risks	1. Oil and gas terminals 2. Pipelines (Trunk lines (12 – 30”) and Flow line or bulk lines (6 – 8 “) 3. Flow stations 4. Oil-well(s) 5. Loading Bay 6. Transformers and High voltage cables 7. Roads and Bridges

Step 2 is the pairwise comparison of infrastructures with STRICT RESPECT to a criterion and the GOAL. Two elements (**A** and **B**) are to be pairwise compared using the Saaty numerical scale (1 – 9; defined in the table below). Depending on how you consider one element to be more important in terms of **VULNERABILITY** to climate impact, please tick appropriate boxes**.**

Numerical Scale	Verbal scale
1	Equally important (A = B)
3	Moderately important (A is slightly important than B)
5	Strongly important (A is strongly important than B)
7	Very strongly important (A very strongly important than B)
9	Extremely important (A is extremely important than B)
2,4,6,8	Intermediate values

Step 1 instance; if you think criterion **“A”** is **MODERATELY IMPORTANT** compared to **“B”** with respect to the VULNERABILITY OF OIL/GAS INFRASTRUCTURES; then tick the box under “A” and box **“3” to the right. But if “B” is MODERATELY IMPORTANT, tick the box under “B” and still box “3” to the left of the chart.**
Step 2 instance, if you think **INFRASTRUCTURE “B”** is **STRONGLY IMPORTANT** compare to **INFRASTRUCTURE “A”** with particular respect to a criterion, tick the box **under “A” and box “5” to** the right. If the reverse applies, tick box under “B” and box **“5”** to the right of chart appropriately.

STEP 1; Please pairwise compare the following **CRITERIA"** to determine their importance in ASSESSING VULNERABILITY OF INFRASTRUCTURES

CRITERION A	CRITERION B	EQUALLY IMPORTANT	MODERATELY IMPORTANT	STRONGLY IMPORTANT	VERY STRONGLY IMPORTANT	EXTREMELY IMPORTANT
Exposure	Presence of Burdens	1	3	5	7	9
Exposure	Criticality	1	3	5	7	9
Exposure	Proximity	1	3	5	7	9
Exposure	Adaptive Capacity	1	3	5	7	9
Exposure	Age of Infrastructure	1	3	5	7	9
Exposure	Interdependence	1	3	5	7	9
Presence of Burdens	Criticality	1	3	5	7	9
Presence of Burdens	Proximity	1	3	5	7	9
Presence of Burdens	Adaptive Capacity	1	3	5	7	9
Presence of Burdens	Age of Infrastructure	1	3	5	7	9
Presence of Burdens	Interdependence	1	3	5	7	9

Criticality	Proximity	1	3	5	7	9
Criticality	Adaptive Capacity	1	3	5	7	9
Criticality	Age of Infrastructure	1	3	5	7	9
Criticality	Interdependence	1	3	5	7	9
Proximity	Adaptive Capacity	1	3	5	7	9
Proximity	Age of Infrastructure	1	3	5	7	9
Proximity	Interdependence	1	3	5	7	9
Adaptive Capacity	Age of Infrastructure	1	3	5	7	9
Adaptive Capacity	Interdependence	1	3	5	7	9
Age of Infrastructure	Interdependence	1	3	5	7	9

STEP 2; in the next step, please pairwise compare the infrastructures with respect to the criteria in the black box and repeated in every cell. NOTE that **YOU WILL BE DECIDING WHICH INFRASTRUCTURE IS MORE VULNERABLE** with respect to the **CRITERIA UNDER CONSIDERATION**. Make your decision by awarding a score between 1 and 9 and tick the corresponding box.

CRITERION A	CRITERION B	EQUALLY IMPORTANT	MODERATELY IMPORTANT	STRONGLY IMPORTANT	VERY STRONGLY IMPORTANT	EXTREMELY IMPORTANT
1. ADAPTIVE CAPACITY						
Terminals ☐	Pipelines ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Terminals ☐	Flow stations ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Terminals ☐	Oil well ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Terminals ☐	Jetties ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Terminals ☐	Transformers/HVC ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Terminals ☐	**Roads & Bridges** ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Pipelines ☐	Flow stations ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Pipelines ☐	Oil well ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Pipelines ☐	Jetties ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9

Pipelines	Transformers/HVC	1	3	5	7	9
Pipelines	Roads & Bridges	1	3	5	7	9
Flow stations	Oil well	1	3	5	7	9
Flow stations	Jetties	1	3	5	7	9
Flow stations	Transformers/HVC	1	3	5	7	9
Flow stations	Roads & Bridges	1	3	5	7	9
Oil well	Jetties	1	3	5	7	9
Oil well	Transformers/HVC	1	3	5	7	9
Oil well	Roads & Bridges	1	3	5	7	9
Jetties	Transformers/HVC	1	3	5	7	9
Jetties	Roads & Bridges	1	3	5	7	9
Transformers/HVC	Roads & Bridges	1	3	5	7	9

2. AGE OF INFRASTRUCTURE						
CRITERION A	**CRITERION B**	**EQUALLY IMPORTANT**	**MODERATELY IMPORTANT**	**STRONGLY IMPORTANT**	**VERY STRONGLY IMPORTANT**	**EXTREMELY IMPORTANT**
Terminals	Pipelines	1	3	5	7	9
Terminals	Flow stations	1	3	5	7	9
Terminals	Oil well	1	3	5	7	9
Terminals	Jetties	1	3	5	7	9
Terminals	**Transformers/HVC**	1	3	5	7	9
Terminals	Roads & Bridges	1	3	5	7	9
Pipelines	Flow stations	1	3	5	7	9
Pipelines	Oil well	1	3	5	7	9
Pipelines	Jetties	1	3	5	7	9
Pipelines	Transformers/HVC	1	3	5	7	9

Pipelines	Roads & Bridges	1	3	5	7	9
Flow stations	Oil well	1	3	5	7	9
Flow stations	Jetties	1	3	5	7	9
Flow stations	**Transformers/HVC**	1	3	5	7	9
Flow stations	Roads & Bridges	1	3	5	7	9
Oil well	Jetties	1	3	5	7	9
Oil well	**Transformers/HVC**	1	3	5	7	9
Oil well	Roads & Bridges	1	3	5	7	9
Jetties	**Transformers/HVC**	1	3	5	7	9
Jetties	Roads & Bridges	1	3	5	7	9
Transformers/HVC	Roads & Bridges	1	3	5	7	9

3. INTERDEPENDENCE

CRITERION A	CRITERION B	EQUALLY IMPORTANT	MODERATELY IMPORTANT	STRONGLY IMPORTANT	VERY STRONGLY IMPORTANT	EXTREMELY IMPORTANT
Terminals	Pipelines	1	3	5	7	9
Terminals	Flow stations	1	3	5	7	9
Terminals	Oil well	1	3	5	7	9
Terminals	Jetties	1	3	5	7	9
Terminals	**Transformers/HVC**	1	3	5	7	9
Terminals	Roads & Bridges	1	3	5	7	9
Pipelines	Flow stations	1	3	5	7	9
Pipelines	Oil well	1	3	5	7	9
Pipelines	Jetties	1	3	5	7	9
Pipelines	Transformers/HVC	1	3	5	7	9
Pipelines	Roads & Bridges	1	3	5	7	9

Flow stations	Oil well	1	3	5	7	9
Flow stations	Jetties	1	3	5	7	9
Flow stations	Transformers/HVC	1	3	5	7	9
Flow stations	Roads & Bridges	1	3	5	7	9
Oil well	Jetties	1	3	5	7	9
Oil well	Transformers/HVC	1	3	5	7	9
Oil well	Roads & Bridges	1	3	5	7	9
Jetties	Transformers/HVC	1	3	5	7	9
Jetties	Roads & Bridges	1	3	5	7	9
Transformers/HVC	Roads & Bridges	1	3	5	7	9

4. PRESENCE OF BURDENS

CRITERION A	CRITERION B	EQUALLY IMPORTANT	MODERATELY IMPORTANT	STRONGLY IMPORTANT	VERY STRONGLY IMPORTANT	EXTREMELY IMPORTANT

Terminals	Pipelines	1	3	5	7	9
Terminals	Flow stations	1	3	5	7	9
Terminals	Oil well	1	3	5	7	9
Terminals	Jetties	1	3	5	7	9
Terminals	**Transformers/HVC**	1	3	5	7	9
Terminals	Roads & Bridges	1	3	5	7	9
Pipelines	Flow stations	1	3	5	7	9
Pipelines	Oil well	1	3	5	7	9
Pipelines	Jetties	1	3	5	7	9
Pipelines	**Transformers/HVC**	1	3	5	7	9
Pipelines	Roads & Bridges	1	3	5	7	9
Flow stations	Oil well	1	3	5	7	9

Flow stations	Jetties	1	3	5	7	9
Flow stations	**Transformers/HVC**	1	3	5	7	9
Flow stations	Roads & Bridges	1	3	5	7	9
Oil well	Jetties	1	3	5	7	9
Oil well	**Transformers/HVC**	1	3	5	7	9
Oil well	Roads & Bridges	1	3	5	7	9
Jetties	**Transformers/HVC**	1	3	5	7	9
Jetties	Roads & Bridges	1	3	5	7	9
Transformers/HVC	Roads & Bridges	1	3	5	7	9

5. EXPOSURE

CRITERION A	CRITERION B	EQUALLY IMPORTANT	MODERATELY IMPORTANT	STRONGLY IMPORTANT	VERY STRONGLY IMPORTANT	EXTREMELY IMPORTANT
Terminals	Pipelines	1	3	5	7	9

Terminals	Flow stations	1	3	5	7	9
Terminals	Oil well	1	3	5	7	9
Terminals	Jetties	1	3	5	7	9
Terminals	**Transformers/HVC**	1	3	5	7	9
Terminals	Roads & Bridges	1	3	5	7	9
Pipelines	Flow stations	1	3	5	7	9
Pipelines	Oil well	1	3	5	7	9
Pipelines	Jetties	1	3	5	7	9
Pipelines	**Transformers/HVC**	1	3	5	7	9
Pipelines	Roads & Bridges	1	3	5	7	9
Flow stations	Oil well	1	3	5	7	9
Flow stations	Jetties	1	3	5	7	9

Flow stations	Transformers/HVC	1	3	5	7	9
Flow stations	Roads & Bridges	1	3	5	7	9
Oil well	Jetties	1	3	5	7	9
Oil well	Transformers/HVC	1	3	5	7	9
Oil well	Roads & Bridges	1	3	5	7	9
Jetties	Transformers/HVC	1	3	5	7	9
Jetties	Roads & Bridges	1	3	5	7	9
Transformers/HVC	Roads & Bridges	1	3	5	7	9

6. CRITICALITY

CRITERION A	CRITERION B	EQUALLY IMPORTANT	MODERATELY IMPORTANT	STRONGLY IMPORTANT	VERY STRONGLY IMPORTANT	EXTREMELY IMPORTANT
Terminals	Pipelines	1	3	5	7	9
Terminals	Flow stations	1	3	5	7	9
Terminals	Oil well	1	3	5	7	9

Terminals	Jetties	1	3	5	7	9
Terminals	**Transformers/HVC**	1	3	5	7	9
Terminals	Roads & Bridges	1	3	5	7	9
Pipelines	Flow stations	1	3	5	7	9
Pipelines	Oil well	1	3	5	7	9
Pipelines	Jetties	1	3	5	7	9
Pipelines	**Transformers/HVC**	1	3	5	7	9
Pipelines	Roads & Bridges	1	3	5	7	9
Flow stations	Oil well	1	3	5	7	9
Flow stations	Jetties	1	3	5	7	9
Flow stations	**Transformers/HVC**	1	3	5	7	9
Flow stations	Roads & Bridges	1	3	5	7	9

Oil well	Jetties	1	3	5	7	9
Oil well	**Transformers/HVC**	1	3	5	7	9
Oil well	Roads & Bridges	1	3	5	7	9
Jetties	**Transformers/HVC**	1	3	5	7	9
Jetties	Roads & Bridges	1	3	5	7	9
Transformers/HVC	Roads & Bridges	1	3	5	7	9

7. PROXIMITY

CRITERION A	CRITERION B	EQUALLY IMPORTANT	MODERATELY IMPORTANT	STRONGLY IMPORTANT	VERY STRONGLY IMPORTANT	EXTREMELY IMPORTANT
Terminals	Pipelines	1	3	5	7	9
Terminals	Flow stations	1	3	5	7	9
Terminals	Oil well	1	3	5	7	9
Terminals	Jetties	1	3	5	7	9

Terminals ☐	Transformers/HVC ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Terminals ☐	Roads & Bridges ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Pipelines ☐	Flow stations ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Pipelines ☐	Oil well ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Pipelines ☐	Jetties ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Pipelines ☐	Transformers/HVC ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Pipelines ☐	Roads & Bridges ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Flow stations ☐	Oil well ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Flow stations ☐	Jetties ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Flow stations ☐	Transformers/HVC ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Flow stations ☐	Roads & Bridges ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Oil well ☐	Jetties ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9

Oil well ☐	**Transformers/HVC** ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Oil well ☐	Roads & Bridges ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Jetties ☐	**Transformers/HVC** ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Jetties ☐	Roads & Bridges ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9
Transformers/HVC ☐	Roads & Bridges ☐	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9

PLEASE THANK YOU SO MUCH FOR YOUR TIME

RESULTS FROM AHAP CRITICALITY ANALYSIS

Appendix VII Pairwise comparison of Economic sub-criteria

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	2	Number of criteria (2 to 10)	Scale: 1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α: 0.15	Consensus: 72.7%
p=	0	selected Participant (0=consol.)	2 7	Consolidated

Objective PAIRWISE COMPARISON OF ECONOMIC SUB CRITERIA

Author

Date

Thresh: 1E-07 Iterations: 13 EVM check: 1.5E-07

Table

	Criterion	Comment	Weights	Rk
1	Replacement Cost		55.7%	1
2	Societal Relevance		44.2%	2
3	Criterion 3		0.0%	
4	Criterion 4		0.0%	
5	Criterion 5		0.0%	
6	Criterion 6		0.0%	
7	Criterion 7		0.0%	
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue		lambda:	1.999
Consistency Ratio	0.37	GCI: n/a	CR: 0.1%

Matrix

		Replacement Cost 1	Societal Relevance 2	Criterion 3 3	Criterion 4 4	Criterion 5 5	Criterion 6 6	Criterion 7 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Replacement Cost	1	-	1 1/4	-	-	-	-	-	-	-	-	55.73%
Societal Relevance	2	4/5	-	-	-	-	-	-	-	-	-	44.22%
Criterion 3	3	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 4	4	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 5	5	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 6	6	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 7	7	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.01%
0	9	-	-	-	-	-	-	-	-	-	-	0.01%
0	10	-	-	-	-	-	-	-	-	-	-	0.01%

by K. Goepel ECONOMIC_TWO_CRITERIA_AHPcalc-2016-05-04 - Copy.xlsx-Summary

Appendix VIII Pairwise comparison of Engineering sub-criteria

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	2	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α:	0.15	Consensus: **78.0%**
p=	0	selected Participant (0=consol.)	2	7	**Consolidated**

Objective PAIRWISE COMPARISON OF ENGINEERING CRITERIA

Author

Date

Thresh: 1E-07 Iterations: 13 EVM check: 1.5E-07

Table

	Criterion	Comment	Weights	Rk
1	Availability of Altern		46.8%	2
2	Cost of Alternatives		53.2%	1
3	Criterion 3		0.0%	
4	Criterion 4		0.0%	
5	Criterion 5		0.0%	
6	Criterion 6		0.0%	
7	Criterion 7		0.0%	
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue lambda: **1.999**

Consistency Ratio 0.37 GCI: n/a CR: 0.1%

Matrix

		Availability of Alternatives 1	Cost of Alternatives 2	Criterion 3 3	Criterion 4 4	Criterion 5 5	Criterion 6 6	Criterion 7 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Availability of Alternatives	1	-	7/8	-	-	-	-	-	-	-	-	46.76%
Cost of Alternatives	2	1 1/7	-	-	-	-	-	-	-	-	-	53.19%
Criterion 3	3	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 4	4	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 5	5	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 6	6	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 7	7	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.01%
0	9	-	-	-	-	-	-	-	-	-	-	0.01%
0	10	-	-	-	-	-	-	-	-	-	-	0.01%

by K. Goepel ENGINEERING_TWO_CRITERIA_AHPcalc-2016-05-04 - Copy.xlsx-Summary

Appendix IX Pairwise comparison of Environment sub-criteria

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 04.05.2016 Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	2	Number of criteria (2 to 10)	Scale: 1		AHP 1-9
N=	19	Number of Participants (1 to 20)	α: 0.15	Consensus:	81.8%
p=	0	selected Participant (0=consol.)	2 7		Consolidated

Objective PAIRWISE COMPARISON OF ENVIRONMENTAL SUB CRITERIA

Author

Date Thresh: 1E-07 Iterations: 13 EVM check: 1.4E-07

Table

	Criterion	Comment	Weights	Rk
1	Impact on Human I		41.2%	2
2	Impact on Ecosyste		58.7%	1
3	Criterion 3		0.0%	
4	Criterion 4		0.0%	
5	Criterion 5		0.0%	
6	Criterion 6		0.0%	
7	Criterion 7		0.0%	
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue		lambda:	1.999
Consistency Ratio	0.37 GCI: n/a	CR:	0.1%

Matrix

		Impact on Human Health 1	Impact on Ecosystem 2	Criterion 3 3	Criterion 4 4	Criterion 5 5	Criterion 6 6	Criterion 7 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Impact on Human	1	-	5/7	-	-	-	-	-	-	-	-	41.21%
Impact on Ecosystem	2	1 3/7	-	-	-	-	-	-	-	-	-	58.75%
Criterion 3	3	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 4	4	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 5	5	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 6	6	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 7	7	-	-	-	-	-	-	-	-	-	-	0.01%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.01%
0	9	-	-	-	-	-	-	-	-	-	-	0.01%
0	10	-	-	-	-	-	-	-	-	-	-	0.01%

by K. Goepel ENVIRONMENTAL_TWO_CRITERIA_AHPcalc-2016-05-04 - Copy.xlsx-Summary

Appendix XI Pairwise comparison of 4 Major criticality criteria

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	4	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α:	0.15	Consensus: **74.1%**
p=	0	selected Participant (0=consol.)	2	7	**Consolidated**

Objective MAJOR 4 XRITERIA FOR CRITICALITY ASSESSMENT

Author JUSTIN UDIE

Date

Thresh: 1E-07 Iterations: 6 EVM check: 1.7E-08

Table

	Criterion	Comment	Weights	Rk
1	Interdependence		13.8%	3
2	Economic Niche		39.5%	1
3	Ecological Concern		37.1%	2
4	Engineering Ability		9.6%	4
5	Criterion 5		0.0%	
6	Criterion 6		0.0%	
7	Criterion 7		0.0%	
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue		lambda:	**4.030**
Consistency Ratio	0.37 GCI: 0.04	CR:	1.1%

Matrix

		Interdependence 1	Economic Niche 2	Ecological Concern 3	Engineering Ability 4	Criterion 5 5	Criterion 6 6	Criterion 7 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Interdependence	1	-	1/3	1/3	1 2/3	-	-	-	-	-	-	13.80%
Economic Niche	2	2 4/5	-	1 2/7	3 1/2	-	-	-	-	-	-	39.54%
Ecological Concern	3	3 1/4	7/9	-	3 4/5	-	-	-	-	-	-	37.06%
Engineering Ability	4	3/5	2/7	1/4	-	-	-	-	-	-	-	9.60%
Criterion 5	5	-	-	-	-	-	-	-	-	-	-	0.00%
Criterion 6	6	-	-	-	-	-	-	-	-	-	-	0.00%
Criterion 7	7	-	-	-	-	-	-	-	-	-	-	0.00%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel MAJOR_FOUR_AHPcalc-2016-05-04.xlsx-Summary

Appendix XII Pairwise comparison of 7 criticality criterion

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α: 0.15	Consensus:	85.3%
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective Pairwise Comparing ALL Criteria for Criticality Assessment

Author Justin Udie

Date

Thresh: 1E-07 Iterations: 4 EVM check: 2.6E-08

Table

	Criterion	Comment	Weights	Rk
1	Interdependence		7.4%	4
2	Replacement cost		6.8%	5
3	Societal Relevance		12.6%	3
4	Impact on Human		26.3%	2
5	Impact on Ecosyst		36.5%	1
6	Availability of Alter		5.2%	6
7	Cost of Alternatives		5.1%	7
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue lambda: 7.241

Consistency Ratio 0.37 GCI: 0.11 CR: 3.0%

Matrix

		Interdependence 1	Replacement cost 2	Societal Relevance 3	Impact on Human Health 4	Impact on Ecosystem 5	Availability of Alternatives 6	Cost of Alternatives 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Interdependence	1	-	1 2/7	1/2	1/5	1/6	2 1/2	1 2/5	-	-	-	7.40%
Replacement cost	2	7/9	-	3/7	1/3	1/4	1 4/9	1 2/9	-	-	-	6.84%
Societal Relevance	3	2 1/5	2 3/8	-	1/3	2/9	3	2 2/3	-	-	-	12.63%
Impact on Human	4	5	3 1/3	3	-	1/2	4 1/3	5	-	-	-	26.26%
Impact on Ecosystem	5	5 6/7	3 5/7	4 4/7	2	-	5	5	-	-	-	36.53%
Availability of Alternatives	6	2/5	2/3	1/3	1/4	1/5	-	1 2/5	-	-	-	5.19%
Cost of Alternatives	7	5/7	5/6	3/8	1/5	1/5	5/7	-	-	-	-	5.14%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel ALL_SEVEN_CRITERIA_AHPcalc-2016-05-04.xlsx-Summary

Appendix XIII Criticality based on "Societal Relevance"

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale: 1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α: 0.15	Consensus: **76.4%**
p=	0	selected Participant (0=consol.)	2 7	**Consolidated**

Objective CRITICALITY ASSESSMENT BASED ON SOCIETAL RELEVANCE

Author

Date Thresh: 1E-07 Iterations: 4 EVM check: 5.3E-09

Table

	Criterion	Comment	Weights	Rk
1	Terminal		23.7%	2
2	Pipeline		5.3%	5
3	Flow Station		16.4%	4
4	Oil Well		4.0%	6
5	Loading Bay		3.7%	7
6	Transformer/HVC		21.1%	3
7	Roads and Bridges		25.9%	1
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue lambda: **7.091**

Consistency Ratio 0.37 GCI: 0.04 CR: 1.1%

Matrix

		Terminal 1	Pipeline 2	Flow Station 3	Oil Well 4	Loading Bay 5	Transformer/HVC 6	Roads and Bridges 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Terminal	1	-	3 5/9	2 1/3	6	6	1	5/6	-	-	-	23.67%
Pipeline	2	2/7	-	1/4	1 1/5	1 1/4	2/7	2/9	-	-	-	5.27%
Flow Station	3	3/7	3 4/5	-	5 1/6	5 2/5	4/5	1/2	-	-	-	16.40%
Oil Well	4	1/6	5/6	1/5	-	1 1/5	1/5	1/6	-	-	-	3.99%
Loading Bay	5	1/6	4/5	1/5	5/6	-	1/6	1/6	-	-	-	3.68%
Transformer/HVC	6	1	3 1/2	1 1/4	5 3/7	6	-	4/5	-	-	-	21.14%
Roads and Bridges	7	1 1/5	4 4/9	2	5 6/7	6	1 1/4	-	-	-	-	25.86%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel 1SOCIETAL RELEVANCE_calc-2016-05-04.xlsx-Summary

Appendix XIV Criticality based on "Replacement Cost"

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α:	0.15	Consensus: **95.7%**
p=	0	selected Participant (0=consol.)	2	7	**Consolidated**

Objective CRITICALITY ASSESSMENT BASED ON REPLACEMENT COST

Author JUSTIN UDIE

Date

Thresh: 1E-07 Iterations: 5 EVM check: 5.4E-08

Table

	Criterion	Comment	Weights	Rk
1	Terminal		51.6%	1
2	Pipeline		6.0%	5
3	Flow Station		21.8%	2
4	Oil Well		3.3%	7
5	Loading Bay		3.8%	6
6	transformers/HVC		6.3%	4
7	Roads and Bridges		7.2%	3
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue			lambda:	**7.397**
Consistency Ratio	0.37	GCI: 0.18	CR:	4.9%

Matrix

		Terminal 1	Pipeline 2	Flow Station 3	Oil Well 4	Loading Bay 5	transformers/HVC 6	Roads and Bridges 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Terminal	1	-	7 4/5	6 1/2	8	8	7 2/9	5 1/2	-	-	-	51.59%
Pipeline	2	1/8	-	1/5	2	1 5/7	7/8	1 1/5	-	-	-	5.96%
Flow Station	3	1/6	5 1/6	-	5 2/3	6	4 4/7	4 2/9	-	-	-	21.84%
Oil Well	4	1/8	1/2	1/6	-	3/4	2/5	3/8	-	-	-	3.29%
Loading Bay	5	1/8	3/5	1/6	1 3/8	-	3/5	1/3	-	-	-	3.84%
transformers/HVC	6	1/7	1 1/7	2/9	2 3/5	1 5/8	-	1	-	-	-	6.33%
Roads and Bridges	7	1/6	5/6	1/4	2 3/4	2 4/5	1	-	-	-	-	7.16%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel 2REPLACEMENT_COST_AHP_calc-2016-05-04.xlsx-Summary

Appendix XV Criticality based on "Interdependence"

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α:	0.15	Consensus: 91.1%
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective Interdependence as criteria for criticality assessment of incfrassructures

Author Justin Udie

Date 17-Feb-17 Thresh: 1E-07 Iterations: 4 EVM check: 4.2E-08

Table

	Criterion	Comment	Weights	Rk
1	Terminal		33.4%	1
2	Pipelines		12.4%	3
3	Flow Stations		29.3%	2
4	Oil Well		4.0%	6
5	Loading Bays		3.1%	7
6	Transformers/HVC		10.1%	4
7	Roads/Bridges		7.6%	5
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue		lambda:	7.310
Consistency Ratio	0.37 GCI: 0.14	CR:	3.9%

Matrix

		Terminal 1	Pipelines 2	Flow Stations 3	Oil Well 4	Loading Bays 5	Transformers/ HVC 6	Roads/Bridges 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Terminal	1	-	4 2/3	1 1/4	6	6 1/4	3 8/9	4 2/5	-	-	-	33.44%
Pipelines	2	1/5	-	1/3	3 1/2	4 7/9	1 3/5	2 1/4	-	-	-	12.43%
Flow Stations	3	4/5	3 1/4	-	5 2/5	6 2/3	4 1/4	4 1/3	-	-	-	29.34%
Oil Well	4	1/6	2/7	1/5	-	1 5/6	2/7	1/3	-	-	-	4.05%
Loading Bays	5	1/6	1/5	1/7	5/9	-	1/4	1/3	-	-	-	3.06%
Transformers /HVC	6	1/4	5/8	1/4	3 1/2	4 1/8	-	1 3/4	-	-	-	10.07%
Roads/Bridge s	7	2/9	4/9	1/4	3	3 1/3	4/7	-	-	-	-	7.62%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel 3INTERDEPENDENCE_AHPcalc-2016-05-04.xlsx-Summary

Appendix XVI Criticality based on "Replacement cost"

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n= 7	Number of criteria (2 to 10)	Scale: 1		AHP 1-9
N= 19	Number of Participants (1 to 20)	α: 0.15	Consensus:	**95.7%**
p= 0	selected Participant (0=consol.)	2 7		**Consolidated**

Objective CRITICALITY ASSESSMENT BASED ON REPLACEMENT COST

Author JUSTIN UDIE

Date

Thresh: 1E-07 Iterations: 5 EVM check: 5.4E-08

Table

	Criterion	Comment	Weights	Rk
1	Terminal		51.6%	1
2	Pipeline		6.0%	5
3	Flow Station		21.8%	2
4	Oil Well		3.3%	7
5	Loading Bay		3.8%	6
6	transformers/HVC		6.3%	4
7	Roads and Bridges		7.2%	3
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue lambda: **7.397**

Consistency Ratio 0.37 GCI: 0.18 CR: 4.9%

Matrix

		Terminal 1	Pipeline 2	Flow Station 3	Oil Well 4	Loading Bay 5	transformers/HVC 6	Roads and Bridges 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Terminal	1	-	7 4/5	6 1/2	8	8	7 2/9	5 1/2	-	-	-	51.59%
Pipeline	2	1/8	-	1/5	2	1 5/7	7/8	1 1/5	-	-	-	5.96%
Flow Station	3	1/6	5 1/6	-	5 2/3	6	4 4/7	4 2/9	-	-	-	21.84%
Oil Well	4	1/8	1/2	1/6	-	3/4	2/5	3/8	-	-	-	3.29%
Loading Bay	5	1/8	3/5	1/6	1 3/8	-	3/5	1/3	-	-	-	3.84%
transformers/HVC	6	1/7	1 1/7	2/9	2 3/5	1 5/8	-	1	-	-	-	6.33%
Roads and Bridges	7	1/6	5/6	1/4	2 3/4	2 4/5	1	-	-	-	-	7.16%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel 2REPLACEMENT_COST_AHP_calc-2016-05-04.xlsx-Summary

Appendix XVII Criticality based on "Impact on Human Health and Safety"

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α:	0.15	Consensus: **74.6%**
p=	0	selected Participant (0=consol.)	2	7	**Consolidated**

Objective CRITICALITY DUE TO IMPACT ON HUMAN HEALTH AND SAFETY

Author

Date

Thresh: 1E-07 Iterations: 4 EVM check: 1.9E-08

Table

	Criterion	Comment	Weights	Rk
1	Terminal		17.9%	3
2	Pipeline		10.5%	5
3	Flow Station		13.5%	4
4	Oil Well		4.7%	6
5	Loading Bay		3.4%	7
6	tramsformers/HVC		22.1%	2
7	Roads/Bridges		27.8%	1
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue		lambda:	**7.194**
Consistency Ratio	0.37	GCI: 0.09	CR: 2.4%

Matrix

		Terminal 1	Pipeline 2	Flow Station 3	Oil Well 4	Loading Bay 5	tramsformers/HVC 6	Roads/Bridges 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Terminal	1	-	2 5/7	1 7/8	3 1/3	4 1/2	1/2	1/2	-	-	-	17.94%
Pipeline	2	3/8	-	5/9	3 5/7	3 7/8	1/2	1/3	-	-	-	10.52%
Flow Station	3	1/2	1 4/5	-	3 3/5	4	1/2	1/2	-	-	-	13.54%
Oil Well	4	2/7	1/4	2/7	-	1 5/7	1/4	1/5	-	-	-	4.69%
Loading Bay	5	2/9	1/4	1/4	4/7	-	1/5	1/6	-	-	-	3.45%
tramsformers /HVC	6	1 6/7	2 1/6	2	3 2/3	5 1/3	-	2/3	-	-	-	22.09%
Roads/Bridge s	7	2	2 3/4	2	5 3/8	6 3/8	1 4/9	-	-	-	-	27.78%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel 4IMPACT_ON_HEALTH_AND_SAFETY_calc-2016-05-04.xlsx-Summary

Appendix XVIII Criticality based on "Impact on Ecosystem"

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α:	0.15	Consensus: **95.5%**
p=	0	selected Participant (0=consol.)	2	7	**Consolidated**

Objective Criticality Assessement based on IMPACT ON ECOSYSTEM

Author

Date

Thresh: 1E-07 Iterations: 5 EVM check: 1.8E-08

Table

	Criterion	Comment	Weights	Rk
1	Terminal		27.1%	2
2	Pipeline		27.9%	1
3	Flow Station		21.5%	3
4	Oil Well		11.0%	4
5	Loading Bay		2.5%	7
6	Transformers/HVC		5.7%	5
7	Roads and Bridges		4.2%	6
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue lambda: **7.368**

Consistency Ratio 0.37 GCI: 0.17 CR: 4.6%

Matrix

		Terminal 1	Pipeline 2	Flow Station 3	Oil Well 4	Loading Bay 5	Transformers/ HVC 6	Roads and Bridges 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Terminal	1	-	1	1 1/2	3 4/9	7 7/9	5 3/8	5 2/5	-	-	-	27.09%
Pipeline	2	1	-	2	4 1/6	6 2/3	4 3/5	5	-	-	-	27.93%
Flow Station	3	2/3	1/2	-	3 3/7	6 5/7	5	4 6/7	-	-	-	21.49%
Oil Well	4	2/7	1/4	2/7	-	5 1/2	3 1/7	4 1/9	-	-	-	11.01%
Loading Bay	5	1/8	1/7	1/7	1/5	-	2/7	2/5	-	-	-	2.54%
Transformers /HVC	6	1/5	2/9	1/5	1/3	3 5/8	-	2	-	-	-	5.70%
Roads and Bridges	7	1/5	1/5	1/5	1/4	2 1/2	1/2	-	-	-	-	4.24%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

Appendix XIX Criticality based on “Cost of Alternatives”

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale: 1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α: 0.15	Consensus: 78.4%
p=	0	selected Participant (0=consol.)	2 7	Consolidated

Objective CRITICALITY ASSESSMENT DUE TO COST OF ALTERNATIVES

Author JUSTIN UDIE

Date 27-Feb-17 Thresh: 1E-07 Iterations: 4 EVM check: 2.6E-08

Table

	Criterion	Comment	Weights	Rk
1	Terminal		32.0%	1
2	Pipeline		5.1%	6
3	Flow Station		23.2%	2
4	Oil Well		4.6%	7
5	Loading Bay		15.9%	3
6	Transformers/HVC		10.3%	4
7	Roads and Bridges		8.9%	5
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue		lambda:	7.224
Consistency Ratio	0.37 GCI: 0.10	CR:	2.8%

Matrix

		Terminal 1	Pipeline 2	Flow Station 3	Oil Well 4	Loading Bay 5	Transformers/HVC 6	Roads and Bridges 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Terminal	1	-	4 3/4	2 1/9	4 5/6	2 1/5	3 1/2	3 5/7	-	-	-	32.01%
Pipeline	2	1/5	-	1/5	1 1/3	4/9	3/8	1/3	-	-	-	5.10%
Flow Station	3	1/2	5	-	4 1/2	1 1/4	3	3 3/4	-	-	-	23.19%
Oil Well	4	1/5	3/4	2/9	-	3/8	2/5	1/3	-	-	-	4.62%
Loading Bay	5	4/9	2 1/4	4/5	2 2/3	-	2 1/9	2 2/7	-	-	-	15.89%
Transformers /HVC	6	2/7	2 2/3	1/3	2 4/7	1/2	-	1 4/7	-	-	-	10.31%
Roads and Bridges	7	1/4	2 3/4	1/4	2 4/5	4/9	5/8	-	-	-	-	8.88%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel 6COST_OF_ALTERNATIVE_calc-2016-05-04 - Copy.xlsx-Summary

Appendix XX Criticality based on "Availability of Alternatives"

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 04.05.2016 Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α:	0.15	Consensus: 89.9%
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective CRITICALITY ASSESSMENT BASED ON AVAILABILITY OF ALTERNATIVE SYSTEMS

Author

Date

Thresh: 1E-07 Iterations: 4 EVM check: 7.2E-08

Table

	Criterion	Comment	Weights	Rk
1	Terminal		3.8%	7
2	Pipeline		10.6%	4
3	Flow Station		4.0%	5
4	Oil Well		3.8%	6
5	Loading Bay		27.6%	1
6	Transformers/HVC		23.7%	3
7	Roads and bridges		26.3%	2
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue		lambda:	7.298
Consistency Ratio	0.37 GCI: 0.14	CR:	3.7%

Matrix

		Terminal 1	Pipeline 2	Flow Station 3	Oil Well 4	Loading Bay 5	Transformers/ HVC 6	Roads and bridges 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Terminal	1	-	1/3	1	1	1/6	1/6	1/5	-	-	-	3.83%
Pipeline	2	3 1/9	-	4 5/7	4 5/7	2/9	1/4	1/4	-	-	-	10.65%
Flow Station	3	1	1/5	-	1 1/4	1/7	1/5	1/5	-	-	-	4.00%
Oil Well	4	1	1/5	4/5	-	1/5	1/5	1/6	-	-	-	3.84%
Loading Bay	5	6 2/5	4 2/5	6 3/5	5	-	1 1/5	1	-	-	-	27.63%
Transformers /HVC	6	5 2/3	4 1/4	5	5 1/3	5/6	-	5/7	-	-	-	23.74%
Roads and bridges	7	5 1/2	4 1/6	5 1/8	5 5/9	1	1 3/8	-	-	-	-	26.31%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel 7AVAILABILITY_OF_ALTERNATIVE_calc-2016-05-04 -.xlsx-Summary

RESULTS FROM AHP VULNERABILITY ANALYSIS

Appendix XXI Comparison of 7 vulnerability criteria

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale: 1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α: 0.15	Consensus: **92.1%**
p=	19	selected Participant (0=consol.)	13 124	**Participant 19**

Objective PAIRWISE COMPARISON OF CRITERIA FOR VULNERABILITY ASSESMENT

Author JUSTIN UDIE

Date 1-Mar-17 Thresh: 1E-07 Iterations: 5 EVM check: 2.0E-08

Table

	Criterion	Comment	Weights	Rk
1	Exposure		27.5%	1
2	Presence of Burde		17.1%	3
3	Criticality		12.6%	5
4	Proximity		17.9%	2
5	Adaptive Capacity		3.9%	7
6	Age of Infrastructu		5.6%	6
7	Interdependence		15.4%	4
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue lambda: **7.692**

Consistency Ratio 0.37 GCI: 0.31 CR: 8.6%

Matrix

		Exposure 1	Presence of Burdens 2	Criticality 3	Proximity 4	Adaptive Capacity 5	Age of Infrastructure 6	Interdependence 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Exposure	1	1	3	5	1	5	3	1	-	-	-	27.47%
Presence of Burdens	2	1/3	1	1	1	3	3	3	-	-	-	17.09%
Criticality	3	1/5	1	1	1	3	3	1	-	-	-	12.61%
Proximity	4	1	1	1	1	5	5	1	-	-	-	17.92%
Adaptive Capacity	5	1/5	1/3	1/3	1/5	1	1/3	1/3	-	-	-	3.88%
Age of Infrastructure	6	1/3	1/3	1/3	1/5	3	1	1/5	-	-	-	5.59%
Interdependence	7	1	1/3	1	1	3	5	1	-	-	-	15.43%
Criterion 8	8	-	-	-	-	-	-	-	1	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	1	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	1	0.00%

by K. Goepel 1_Pairwise_Comparison_of_CRITERIA.xlsx-Summary

Appendix XXII Adaptive capacity vulnerability comparison

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α:	0.15	Consensus: **71.0%**
p=		selected Participant (0=consol.)	2	7	**Consolidated**

Objective ADAPTIVE CAPACITY

Author

Date 1-Mar-17 Thresh: 1E-07 Iterations: 4 EVM check: 6.9E-09

Table

	Criterion	Comment	Weights	Rk
1	Pipelines		23.2%	2
2	Flow Station		6.1%	7
3	Terminal		6.1%	6
4	Loading Bay		23.4%	1
5	Transformer/HVC		9.5%	5
6	Road and Bridges		12.1%	4
7	Oil Wells		19.6%	3
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue				lambda:	**7.104**
Consistency Ratio	0.37	GCI:	0.05	CR:	1.3%

Matrix

		Pipelines 1	Flow Station 2	Terminal 3	Loading Bay 4	Transformer/HVC 5	Road and Bridges 6	Oil Wells 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Pipelines	1	-	4 4/7	3 3/8	1	2 5/7	2 1/5	1	-	-	-	23.18%
Flow Station	2	2/9	-	1 2/5	1/3	4/9	3/8	1/3	-	-	-	6.08%
Terminal	3	2/7	5/7	-	1/3	5/8	1/2	1/3	-	-	-	6.10%
Loading Bay	4	1	3	3	-	2 4/5	2 3/8	1 1/3	-	-	-	23.45%
Transformer/HVC	5	3/8	2 2/9	1 5/8	1/3	-	2/3	1/2	-	-	-	9.51%
Road and Bridges	6	1/2	2 2/3	2 1/9	3/7	1 1/2	-	1/2	-	-	-	12.09%
Oil Wells	7	1	3	2 7/8	3/4	2	2	-	-	-	-	19.59%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel 1ADAPTIVE_CAPACITY_CRITERIA_calc-2016-05-04 - Copy.xlsx-Summary

Appendix XXIII Age of Infrastructure vulnerability comparison

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α:	0.15	Consensus: **71.7%**
p=	0	selected Participant (0=consol.)	2	7	**Consolidated**

Objective COMPARE FOR VULNERABILITY DUE TO "AGE OF INFRASTRUCTURE"

Author

Date

Thresh: 1E-07 Iterations: 4 EVM check: 1.4E-08

Table

	Criterion	Comment	Weights	Rk
1	TERMINAL		11.4%	5
2	PIPELINES		27.1%	1
3	FLOW STATIONS		13.4%	4
4	OIL WELL		14.0%	3
5	LOADING BAY		5.8%	7
6	TRANSFORMER/H		10.9%	6
7	ROADS AND BRID		17.5%	2
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue		lambda:	**7.164**
Consistency Ratio	0.37 GCI: 0.08	CR:	2.0%

Matrix

		TERMINAL 1	PIPELINES 2	FLOW STATIONS 3	OIL WELL 4	LOADING BAY 5	TRANSFORM ER/HVC 6	ROADS AND BRIDGES 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
TERMINAL	1	-	7/9	7/9	3/4	1 1/2	1	1/2	-	-	-	11.36%
PIPELINES	2	1 2/7	-	2	2 1/8	3 2/3	3 3/5	2	-	-	-	27.05%
FLOW STATIONS	3	1 2/7	1/2	-	1	2 2/3	1	4/5	-	-	-	13.38%
OIL WELL	4	1 1/3	1/2	1	-	2 3/7	1 3/5	5/7	-	-	-	13.99%
LOADING BAY	5	2/3	1/4	3/8	2/5	-	1/3	3/8	-	-	-	5.82%
TRANSFORMER/HVC	6	1 1/9	2/7	1	5/8	2 8/9	-	1/2	-	-	-	10.88%
ROADS AND BRIDGES	7	1 5/6	1/2	1 1/4	1 2/5	2 2/3	2	-	-	-	-	17.51%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel 2AGE_OF_INFRASTRUCTURE_AHPcalc-2016-05-04.xlsx-Summary

Appendix XXIV Criticality vulnerability comparison

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale: 1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α: 0.15	Consensus: **77.6%**
p=	0	selected Participant (0=consol.)	2 7	**Consolidated**

Objective COMPARE INFRASTRUCTURE VULNERABILITY DUE TO CRITICALITY

Author

Date

Thresh: 1E-07 Iterations: 4 EVM check: 8.1E-08

Table

	Criterion	**Comment**	**Weights**	**Rk**
1	Terminal		19.4%	2
2	Pipeline		19.2%	3
3	Flow Station		28.8%	1
4	Oil Well		7.2%	6
5	Loading Bay		3.8%	7
6	Transformer/HVC		10.5%	5
7	Road and Bridges		11.1%	4
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue			lambda: **7.291**
Consistency Ratio	0.37	GCI: 0.13	CR: 3.6%

Matrix

		Terminal 1	Pipeline 2	Flow Station 3	Oil Well 4	Loading Bay 5	Transformer/HVC 6	Road and Bridges 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Terminal	1	-	1 5/9	1	2 1/2	2 6/7	1 1/2	2	-	-	-	19.42%
Pipeline	2	2/3	-	1/2	3 6/7	4 5/6	2 1/7	2 1/5	-	-	-	19.17%
Flow Station	3	1	2	-	4	5 2/9	3 2/5	3 1/2	-	-	-	28.79%
Oil Well	4	2/5	1/4	1/4	-	3 4/7	3/5	1/2	-	-	-	7.25%
Loading Bay	5	1/3	1/5	1/5	2/7	-	1/4	1/4	-	-	-	3.77%
Transformer/HVC	6	2/3	1/2	2/7	1 2/3	4	-	7/9	-	-	-	10.54%
Road and Bridges	7	1/2	1/2	2/7	2	4	1 2/7	-	-	-	-	11.07%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel 3CRITICALITY_AHPcalc-2016-05-04 - Copy.xlsx-Summary

Appendix XXV Exposure vulnerability comparison

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 04.05.2016 Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α:	0.15	Consensus: 66.9%
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective Compare due to EXPOSURE

Author

Date Thresh: 1E-07 Iterations: 4 EVM check: 7.1E-09

Table

	Criterion	Comment	Weights	Rk
1	Terminal		17.3%	3
2	Pipeline		25.3%	1
3	Flow Station		6.8%	6
4	Oil-Well		6.2%	7
5	Loading Bay		20.3%	2
6	Transformer/HVC		12.1%	4
7	Roads and Bridges		12.0%	5
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue lambda: 7.098

Consistency Ratio 0.37 GCI: 0.05 CR: 1.2%

Matrix

		Terminal 1	Pipeline 2	Flow Station 3	Oil-Well 4	Loading Bay 5	Transformer/HVC 6	Roads and Bridges 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Terminal	1	-	1	2	2 1/7	5/6	1 1/2	1 5/9	-	-	-	17.34%
Pipeline	2	1	-	3 7/9	4	1 3/4	1 7/8	2 2/7	-	-	-	25.25%
Flow Station	3	1/2	1/4	-	1	1/3	1/2	2/3	-	-	-	6.83%
Oil-Well	4	1/2	1/4	1	-	2/7	2/5	4/9	-	-	-	6.15%
Loading Bay	5	1 1/5	4/7	3	3 1/2	-	2 2/7	1 2/3	-	-	-	20.31%
Transformer/HVC	6	2/3	1/2	2 1/8	2 1/2	4/9	-	5/6	-	-	-	12.10%
Roads and Bridges	7	2/3	3/7	1 1/2	2 1/4	3/5	1 1/5	-	-	-	-	12.01%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

Appendix XXVI Interdependence vulnerability comparison

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 04.05.2016 Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α:	0.15	Consensus: 78.5%
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective PAIRWISE COMPARISON DUE TO INTERDEPENDENCE OF INFRASTRUCTURE

Author

Date

Thresh: 1E-07 Iterations: 4 EVM check: 5.4E-09

Table

	Criterion	Comment	Weights	Rk
1	Terminal		34.0%	1
2	Pipeline		16.9%	3
3	Flow Station		10.5%	5
4	Oil Well		5.3%	6
5	Loading Bay		4.4%	7
6	Transformer and H		11.6%	4
7	Roads and Bridges		17.3%	2
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue			lambda:	7.110
Consistency Ratio	0.37	GCI: 0.05	CR:	1.4%

Matrix

		Terminal 1	Pipeline 2	Flow Station 3	Oil Well 4	Loading Bay 5	Transformer and HVC 6	Roads and Bridges 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Terminal	1	-	2 2/3	2 4/5	5	6	3 2/5	2 3/8	-	-	-	34.02%
Pipeline	2	3/8	-	1 3/4	3 2/3	4	1 1/5	1 2/9	-	-	-	16.94%
Flow Station	3	1/3	4/7	-	2 1/3	2 5/7	6/7	1/2	-	-	-	10.49%
Oil Well	4	1/5	1/4	3/7	-	1 2/7	2/5	1/3	-	-	-	5.30%
Loading Bay	5	1/6	1/4	3/8	7/9	-	1/3	1/3	-	-	-	4.40%
Transformer and HVC	6	2/7	5/6	1 1/6	2 3/7	3	-	4/9	-	-	-	11.58%
Roads and Bridges	7	3/7	5/6	2	2 6/7	3 2/7	2 1/4	-	-	-	-	17.28%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel 5INTERDEPENDENCE_OF_INFRASTRUCTURE_AHPcalc-2016-05-04.xlsx-Summary

Appendix XXVII Presence of burdens vulnerability comparison

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	19	Number of Participants (1 to 20)	α:	0.15	Consensus: **90.7%**
p=	0	selected Participant (0=consol.)	2	7	**Consolidated**

Objective COMPARE BASED ON PRESENCE OF BURDENS AROUND THE INFRASTRUCTURE

Author

Date Thresh: 1E-07 Iterations: 4 EVM check: 6.9E-08

Table

	Criterion	Comment	Weights	Rk
1	Terminal		18.3%	2
2	Pipeline		36.0%	1
3	Flow Station		11.2%	4
4	Oil Well		4.8%	6
5	Loading Bay		4.4%	7
6	Transformer/HVC		9.7%	5
7	Roads and Bridges		15.7%	3
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue		lambda:	7.339
Consistency Ratio	0.37 GCI: 0.16	CR:	4.2%

Matrix

		Terminal 1	Pipeline 2	Flow Station 3	Oil Well 4	Loading Bay 5	Transformer/HVC 6	Roads and Bridges 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Terminal	1	-	4/7	1 2/5	2 6/7	3	2 1/2	1 6/7	-	-	-	18.35%
Pipeline	2	1 3/4	-	4 3/4	5 1/3	5	4	3 1/2	-	-	-	35.95%
Flow Station	3	5/7	1/5	-	2 3/7	3 1/6	1 2/5	3/4	-	-	-	11.20%
Oil Well	4	1/3	1/5	2/5	-	1 1/3	2/7	1/4	-	-	-	4.77%
Loading Bay	5	1/3	1/5	1/3	3/4	-	2/7	2/7	-	-	-	4.36%
Transformer/HVC	6	2/5	1/4	5/7	3 3/5	3 3/7	-	1/3	-	-	-	9.66%
Roads and Bridges	7	1/2	2/7	1 3/8	4	3 5/8	3	-	-	-	-	15.72%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel 6PRESENCE_OF_BURDENS_AHP_calc-2016-05-04.xlsx-Summary

Appendix XXVIII Proximity vulnerability comparison

http://bpmsg.com AHP 14/08/2018

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **04.05.2016** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale: 1		AHP 1-9
N=	19	Number of Participants (1 to 20)	α: 0.15	Consensus:	62.4%
p=	0	selected Participant (0=consol.)	2 7		Consolidated

Objective COMPARE INFRASTRUCTURE DUE TO PROXIMITY

Author

Date

Thresh: 1E-07 Iterations: 4 EVM check: 9.6E-09

Table

	Criterion	Comment	Weights	Rk
1	Terminal		12.4%	4
2	Pipelines		25.1%	1
3	Flow Station		10.0%	6
4	Oil Well		7.3%	7
5	Loading Bay		20.0%	2
6	Transformer/HVC		11.8%	5
7	Roads and Bridges		13.4%	3
8	Criterion 8		0.0%	
9		for 9&10 unprotect the input sheets and expand the	0.0%	
10		question section ("+" in row 66)	0.0%	

Result

Eigenvalue			lambda:	7.130
Consistency Ratio	0.37	GCI: 0.06	CR:	1.6%

Matrix

		Terminal 1	Pipelines 2	Flow Station 3	Oil Well 4	Loading Bay 5	Transformer/HVC 6	Roads and Bridges 7	Criterion 8 8	0 9	0 10	normalized principal Eigenvector
Terminal	1	-	4/7	1 1/2	1 2/5	3/4	8/9	1	-	-	-	12.44%
Pipelines	2	1 3/4	-	2 1/3	3 1/3	1 4/9	2 1/5	2 1/6	-	-	-	25.06%
Flow Station	3	2/3	3/7	-	1 1/4	3/4	5/7	2/3	-	-	-	9.98%
Oil Well	4	5/7	1/3	4/5	-	4/9	1/2	4/9	-	-	-	7.32%
Loading Bay	5	1 3/8	2/3	1 1/3	2 1/4	-	2 5/9	2 1/8	-	-	-	20.01%
Transformer/HVC	6	1 1/8	1/2	1 2/5	2 1/7	2/5	-	2/3	-	-	-	11.77%
Roads and Bridges	7	1 1/9	1/2	1 4/9	2 1/5	1/2	1 4/9	-	-	-	-	13.41%
Criterion 8	8	-	-	-	-	-	-	-	-	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	-	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	-	0.00%

by K. Goepel 7PROXIMITY_TO_CLIMATE _RISKS_AHPcalc-2016-05-04 - Copy.xlsx-Summary

APPENDIX: XXIX *Systematic Review*

AUTHORS	TITLE	YEAR PUBLISHED	KEYWORDS	RESEARCH FOCUS	SCOPED INDICATORS	DESIGN	FREQUENCY OF CITATION
Preston B.L., Yuen E.J., Westaway R.M.	Putting vulnerability to climate change on the map: A review of approaches, benefits, and risks	2011	Adaptation; Climate change; Mapping; Vulnerability assessment	spatially-explicit information regarding vulnerability to climate change at the local scale	adaptation actions, vulnerability framed	Mix	159
De Lange H.J., Sala S., Vighi M., Faber J.H.	Ecological vulnerability in risk assessment - A review and perspectives	2010	Ecological vulnerability assessment; Hazard; Hierarchical scale; Organization level; Resilience; Risk	the application of ecological vulnerability analysis in risk assessment and describes new developments in methodology using stakeholders ranking and mapping of the results	ecosystems concern or communities,	Mix	128
Schaeffer R., Szklo A.S., Pereira de Lucena A.F., Moreira Cesar Borba B.S., Pupo Nogueira L.P., Fleming F.P., Troccoli A., Harrison M., Boulahya M.S.	Energy sector vulnerability to climate change: A review	2012	Climate change impacts and risks; Energy system; Vulnerability	Vulnerability of Energy systems to climate change	Vulnerability, adaptation and resilience. The use of these two indicators can portray a picture of the impacts on existing and future hydropower resources, despite the limitations of using the gross potential	Qualitative	126

Vafeidis A.T., Nicholls R.J., McFadden L., Tol R.S.J., Hinkel J., Spencer T., Grashoff P.S., Boot G., Klein R.J.T.	A new global coastal database for impact and vulnerability analysis to sea-level rise	2008	Climate change; Coastal geographic information system (GIS); Data model; Global change; Segmentation	The assessment of the database on the world's coasts, excluding Antarctica, and includes information on more than 80 physical, ecological, and socioeconomic parameters of the coastal zone	heritage sites, administrative units, countries, rivers, tidal basins or estuaries	Qualitative	119
Papathoma-Köhle M., Kappes M., Keiler M., Glade T.	Physical vulnerability assessment for alpine hazards: State of the art and future needs	2011	Avalanches; Debris flows; Floods; Landslides; Rock falls; Vulnerability	Mountain hazards such as landslides, floods and avalanches pose a serious threat to human lives and development and can cause considerable damage to lifelines, critical infrastructure, agricultural lands, housing, public and private infrastructure and assets.	Experts judgement, Risk magnitude, Economic vulnerability, water's presence, water's motion, magnitude and direction, tendency to float, Age and type of building, cost of repair and Building sensitivity (value)	Qualitative	92
Grubesic T.H., Matisziw T.C., Murray A.T., Snediker D.	Comparative approaches for assessing network vulnerability	2008	Critical infrastructure; Graph theory; Interdiction; Networks; Scale-free networks	Analysis and evaluation of network-based critical infrastructure is the assessment of system	Network and interlinked performance, Importance of facility	Qualitative	91

				vulnerability.			
Murray A.T., Matisziw T.C., Grubesic T.H.	A methodological overview of network vulnerability analysis	2008	Infrastructure (Economics), Planning, Management, Research, Transportation, Economic development, Methodology, Military strategy, Public works	Evaluating network infrastructures for potential vulnerabilities is an important component of strategic planning, particularly in the context of managing and mitigating service disruptions	Network to a structured or coordination leads loss of facilities, scenario and location	Mix	73
Webb E.L., Friess D.A., Krauss K.W., Cahoon D.R., Guntensperg en G.R., Phelps J.	A global standard for monitoring coastal wetland vulnerability to accelerated sea-level rise	2013	Sea-level rise, coastal salt-marshes, mangrove forests, vulnerability, elevation	Focuses on how Sea-level rise threatens coastal salt-marshes and mangrove forests around the world, and a key determinant of coastal wetland vulnerability	Extreme weather, surface elevation	Quantitative	70

Bruno Soares M., Gagnon A.S., Doherty R.M.	Conceptual elements of climate change vulnerability assessments: A review	2012	Assessment frameworks; Climate change; Conceptual elements; Integrated vulnerability assessment; Risk assessment	The purpose of this paper is to review the literature on climate change vulnerability and explore and synthesize those conceptual and analytical aspects considered fundamental in a vulnerability assessment in climate change	Human elements, environment system, uncertainty, Historical records of burden	Qualitative	27
Kumar P., Bansod B.K.S., Debnath S.K., Thakur P.K., Ghanshyam C.	Index-based groundwater vulnerability mapping models using hydrogeological settings: A critical evaluation	2015	Contamination; DRASTIC; Groundwater; Vulnerability assessment	This paper reviews the various groundwater vulnerability assessment models developed across the world	Hybridisation of indicators on proximity, sensitivity, adaptive capacity in assessment	Mix	24
Pavlis M., Cummins E., McDonnell K.	Groundwater vulnerability assessment of plant protection products: A review	2010	Plant protection products; Regional scale; Vulnerability assessment	The objective of this article is to review and compare the most important vulnerability assessment methods and tools that have been used in catchment/regional scale studies.	exposure to risk, Capacity, local conditions	Quantitative	19

Nazemi A., Wheater H.S.	Assessing the vulnerability of water supply to changing streamflow conditions	2014	Streamflow regimes; Vulnerability assessment; Water resource systems; Water stress	Assessing the vulnerability of water to conditions arising from streamflow	None in open access		18
Wang B., Ke R.-Y., Yuan X.-C., Wei Y.-M.	China's regional assessment of renewable energy vulnerability to climate change	2014	Climate change; Grey cluster analysis; Renewable energy; Vulnerability; Vulnerability scoping diagram	Renewable energy development as a major response to addressing of climate change and energy security	exposure, sensitivity, social factors, adaptive capacity	Qualitative	15
Reid W.V., Mooney H.A.	The Millennium Ecosystem Assessment: Testing the limits of interdisciplinary and multi-scale science	2016	Environmental assessment, Ecosystem services , Biodiversity and Ecosystem	Interdisciplinary collaboration enabled the valuation of ecosystem services to society.	biodiversity, ecosystems and economies and human health	Qualitative	12
Singh P.K., Tiwari A.K., Panigary B.P., Mahato M.K.	Water quality indices used for water resources vulnerability assessment using GIS technique : A review	2013	GIS; Water quality; Water quality index; WQI's classification	Focus on the presence of contaminants in natural freshwater continues to be one of the most important environmental issues in many areas of the world, where a significant part of population is far away from potable	Low income communities, exposure, socio-economic development, physico-chemical and biological parameters	Mix	12

				water supply.			
Ordóñez C., Duinker P.N.	Assessing the vulnerability of urban forests to climate change	2014	Climate adaptation; Climate change; Climate vulnerability assessment; Urban forest	Climate adaptation is being embraced by many municipalities worldwide. It argues that climate vulnerability assessments are necessary for addressing climate adaptation in urban forests and contribute to successful climate adaptation in cities	Climate exposure, impact, sensitivity, and adaptive capacity,	Qualitative	11

Sebesvari Z., Renaud F.G., Haas S., Tessler Z., Hagenlocher M., Kloos J., Szabo S., Tejedor A., Kuenzer C.	A review of vulnerability indicators for deltaic social–ecological systems	2016	Indicators; Multiple hazards; Social–ecological systems; Sustainable deltas; Vulnerability assessment frameworks	An assessment of the sustainability of deltas worldwide is under threat and consequences of global environmental change (including climate change) and human interventions in deltaic landscapes.	Percentage of change in major land use categories, Subsidence, Coastal slope, Mean accumulation rate, Percentage of farmer-managed populations, livelihoods and poverty, human health, key economic sectors and services, human security, and urban areas, age structure, human health, Density of public infrastructure,	Mix	10
Iqbal J., Gorai A.K., Tirkey P., Pathak G.	Approaches to groundwater vulnerability to pollution: A literature review	2012	Groundwater; literature review; overlay index; process-based simulation; statistical method; vulnerability assessment	formulate a universal technique for predicting groundwater vulnerability	vulnerability range, complexity of infrastructure, strengths and weaknesses (adaptive capacities)	Mix	9
Sharma J., Chaturvedi R.K., Bala G., Ravindranath N.H.	Challenges in vulnerability assessment of forests under climate change	2013	adverse impact, vulnerability of forests, climate change, Forest-management, effective adaptation	assessing the vulnerability of forest ecosystems and Forest-management goals	Interdependence, complexity of infrastructure, strengths and weaknesses (adaptive capacities), linkages	Qualitative	7

Fatemi F., Ardalan A., Aguirre B., Mansouri N., Mohammadfam I.	Social vulnerability indicators in disasters: Findings from a systematic review	2017	Disasters; Indicators; Social vulnerability; Validity	Review of the social vulnerability indices and their validity in disasters within the period 1985–2015 and to develop a suitable classification to make sense of social vulnerability indices in the Iranian context	Exposure, social vulnerability, deficiencies in infrastructure make people s more socially vulnerable (Interdependencies)	Qualitative	6
Zarafshani K., Sharafi L., Azadi H., Van Passel S.	Vulnerability assessment models to drought: Toward a conceptual framework	2016	Assessment; Drought; Factor; Risk management; Vulnerability	Crisis management is the basis of drought mitigation plans. The paper focuses on developing a conceptual framework for designing a vulnerability model to assess farmers' level of vulnerability before, during and after the onset of drought	sensitivity indicators, monetary impact, socioeconomic indicators, environmental causes, capacity of a system to adapt to climate change and adaptation policy	Qualitative	5

Papathanasopoulou E., Queirós A.M., Beaumont N., Hooper T., Nunes J.	What are the local impacts of energy systems on marine ecosystem services: A systematic map protocol	2014	Biodiversity; Ecosystem functions; Ecosystem impacts; Ecosystem Processes; Ecosystem service classifications; Ecosystem service impacts; Energy systems; Habitats; Human health and well-being	how the construction, operation and decommissioning of these energy systems will impact marine ecosystem services, i.e. the services obtained by people from the natural environment such as food provisioning, climate regulation and cultural inspiration. Millennium Ecosystem Assessment (MEA) frameworks are used and a detailed description of the steps taken provided to ensure transparency and replicability	The study sourced databases of publication selected a set of selection criteria including: relevant Exposure, nearness to offshore and coastal systems, Changes in structure, and use of Maps	Qualitative	5
Bhuiyan S.R., Baky A.A.	Digital elevation-based flood hazard and vulnerability study at various return periods in Sirajganj Sadar Upazila, Bangladesh	2014	Frequency analysis; Inundation; Land use; Return period; Risk element; Riverine	The objectives of the study are flood hazard mapping and crops and settlement vulnerability assessment in a low laying riverine flood prone area of Bangladesh	flood magnitudes, low laying lands, distance to shore,	Qualitative	5

				for different flood magnitudes.			
Zaid S.M., Mamoun M.M., Al-Mobark N.M.	Vulnerability assessment of the impact of sea level rise and land subsidence on north Nile Delta region	2014	Land subsidence; North Nile Delta; Sea level rise	A survey of the detailed quantitative assessment of the vulnerability of the Nile Delta coast of Egypt to the impacts of SLR and land subsidence is presented	vulnerable areas of the coastal zone, Human livelihoods, Social systems (tourism), Adaptation capacities of institutions, integration of systems	Mix	5
McNeeley S.M., Even T.L., Gioia J.B.M., Knapp C.N., Beeton T.A.	Expanding vulnerability assessment for public lands: The social complement to ecological approaches	2017	Adaptation; Climate change; Land-based livelihoods; Public lands; Social vulnerability; Vulnerability assessment	climate change vulnerability and adaptation planning in Federal Land Management agencies in the US	strengths and weaknesses of an ecological, social-ecological	Qualitative	4
Barrere M., Badonnel R., Festor O.	Vulnerability assessment in autonomic networks and services: A survey	2014	autonomic computing; computer security; Vulnerability assessment; vulnerability management	The vulnerability management process of autonomic networks and services	Exposure, proximity, presence of burdens	Qualitative	4

Bhave A.G., Mishra A., Raghuwanshi N.S.	A brief review of assessment approaches that support evaluation of climate change adaptation options in the water sector	2014	Climate change; Criteria; Evaluation; Planned adaptation; Water	Focuses on TRANSDICIPLINARY assessment of adapting to changing water resources' availability due to climate change. A synthesis of methods for evaluation reveals four main categories:	We find that important criteria, such as temporal adaptation capacity, and cost of implement ability, have not been explicitly considered in scientific literature.	Qualitative	4
Steenberg J.W.N., Millward A.A., Nowak D.J., Robinson P.J.	A conceptual framework of urban forest ecosystem vulnerability	2017	Ecosystem services; Indicator; Social-ecological system; Urban forest; Vulnerability	propose a theory-based conceptual framework for the assessment of urban forest vulnerability that integrates the biophysical, built, and human components of urban forest ecosystems	(i) exposure, (ii) sensitivity, (iii) adaptive capacity, (iv) Potential impacts (v) Ecosystems,	Qualitative	3
Di Paola G., Aucelli P.P.C., Benassai G., Iglesias J., Rodríguez G., Rosskopf C.M.	The assessment of the coastal vulnerability and exposure degree of Gran Canaria Island (Spain) with a focus on the coastal risk of Las Canteras Beach in Las	2017	Canary Islands; Coastal exposure assessment; Coastal risk assessment; Coastal vulnerability assessment; GIS analysis	The evaluation of coastal vulnerability of the Gran Canaria Island	Exposure Degree, coastal inundation, Socio-economic and damage indexes, Location	Qualitative	2

	Palmas de Gran Canaria						
González-Baheza A., Arizpe O.	Vulnerability assessment for supporting sustainable coastal city development: a case study of La Paz, Mexico	2017	climate change; coastal zone; fragility; indicators; pressure; sustainable development; vulnerability model	Evaluations and monitoring of vulnerability models in coastal areas will assist in formulating environmental policies and guiding decision-makers to address the central tenets for the sustainable development of coastal cities	Exposure, socio-economic factors, very high fragility, physical, environmental and socio-economic, Pressure Index and Fragility/sensitivity	Qualitative	2
Shukla R., Sachdeva K., Joshi P.K.	Demystifying vulnerability assessment of agriculture communities in the Himalayas: a systematic review	2017	Agriculture communities; Himalayas; Systematic review; Vulnerability assessment	systematically review peer-reviewed literature focused on vulnerability assessment of agriculture communities (n = 26) in the five Himalayan countries	vulnerability assessment use social, economic, cultural, institutional, environmental, and physical	Quantitative	
Santos P.P., Tavares A.O., Freire P., Rilo A.	Estuarine flooding in urban areas: enhancing vulnerability	2017	Flood hazard; Multiscale; Risk management; Vulnerability	The assessment of flood risk vulnerability in urban areas	Exposure, estimation of the impact, eco-environmental, economic	Mix	

	assessment				and social dimensions		
Pennetta M., Corbelli V., Gattullo V., Nappi R., Brancato V.M., Gioia D.	Beach vulnerability assessment of a protected area of the Northern Campania coast (Southern Italy)	2017	Carrying capacity; Coastal geomorphology; Dune vulnerability index (DVI); Garigliano River mouth (Campania region; Human impact; Italy)	multidisciplinary study of physical and biotic factors of a coastal sector of southern Italy	human practises, sustainability, socio-cultural carrying capacity, Distant to vulnerable areas	Qualitative	
De Ruiter M.C., Ward P.J., Daniell J.E., Aerts J.C.J.H.	Review Article: A comparison of flood and earthquake vulnerability assessment indicators	2017	vulnerability indicators, vulnerability assessments, physical and social categories, physical attributes, Flood vulnerability studies	extensive literature review to increase understanding of vulnerability indicators used in the disciplines of earthquake- and flood vulnerability assessments	Social, Economic, Environmental, Physical adaptations	Quantitative	
Obodan N.I., Adlutskii V.Y., Gromov V.A.	Vulnerability Assessment of Loaded Thin-Walled Shells Under an External Pulse Action	2017	bifurcation; geometrically and physically nonlinear dynamic behavior; neural network; pulse loading; thin-walled shell; time series; vulnerability	vulnerability assessment of thin-walled shells under pulse action	level of strains, Economic, Environmental factors	Quantitative	

Ogie R.I., Holderness T., Dunn S., Turpin E.	Assessing the vulnerability of hydrological infrastructure to flood damage in coastal cities of developing nations	2017	Coastal cities; Flood; Floodgate; Infrastructure; Network; Vulnerability	Hydrological infrastructure and flood barriers are invaluable assets used for controlling water in flood-prone areas such coastal cities	concepts of exposure, susceptibility and resilience, network nodes of systems	Qualitative	
Han L., Han Q., Ge Y.-X., Sang X.-Q.	Vulnerability assessment of combat aircraft to blast loading	2017	blast kill contours; blast loading; kill criteria; structure dynamic; Vulnerability	aircraft vulnerability assessment because of its destructive damaging effort in short distance encounter	Kill criteria, proximity to blast contours	Qualitative	
Boori M.S., Choudhary K., Kupriyanov A.	Vulnerability evaluation from 1995 to 2016 in central dry zone area of Myanmar	2017	GIS; Principle component analysis; Remote sensing; Vulnerability	focuses on vulnerability assessment using remote sensing (RS) and geographical information system (GIS) technology to develop a numerical model, using spatial principle component analysis (SPCA) in ArcGIS software and evaluate two decade (1995, 2005 & 2016) vulnerability evaluation	Eminence worst of flood risks, Cost implications, interconnectedness	Qualitative	

Zhang Y., Zhang K., Niu Z.	Reservoir-type water source vulnerability assessment: a case study of the Yuqiao Reservoir, China	2016	water source vulnerability, reservoir vulnerability, suitable indexes for vulnerability assessment, AHP and integrated weighting methods	developing a method to assess reservoir-type water source vulnerability (WSV) and adapted the method to the Yuqiao Reservoir	Social threats, potential menace, Regulations and environmental awareness	Quantitative	
Kojekov E.	Report on Issyk-Kul biosphere reserve	2008	Climate change; Cultural landscapes; Global Change in Mountain Regions project; Global warming; GLOCHAMORE; MBR; Mountain Biosphere Reserve; Vulnerability assessment	Assessing the development of policies and projects as well as to capacity building to determine the strategic position for capacity building as new ecological issues. The aim of self-assessment is to identify and analyse national priorities and needs for capacity increase at the individual, institutional and system levels	Sensitivities and priority, and common linkages and problems, Adaptation capacities	Qualitative	

Carpenter S.R., Mooney H.A., Agard J., Capistrano D., Defries R.S., Diaz S., Dietz T., Duraiappah A.K., Oteng-Yeboah A., Pereira H.M., Perrings C., Reid W.V., Sarukhan J., Scholes R.J., Whyte A.	Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment	2009	Ecosystem Assessment, framework for analysing social–ecological systems, effects on human well-being,	Millennium Ecosystem Assessment (MA) introduced a new framework for analysing social-ecological systems that has had wide influence in the policy and scientific communities through criteria assessment process	ecosystem services and human well-being, social systems, complex infrastructure,	Qualitative	935
Shao Y., Wyrwoll K.-H., Chappell A., Huang J., Lin Z., McTainsh G.H., Mikami M., Tanaka T.Y., Wang X., Yoon S.	Dust cycle: An emerging core theme in Earth system science	2011	Aeolian processes; Carbon cycle; Climate change; Dust; Dust cycle; Energy cycle	Our review focuses on (i) the concept of the dust cycle in the context of global biogeochemical cycles; (ii) dust as a climate indicator; (iii) dust modelling; (iv) dust monitoring; and (v) dust parameters.	indicators range from physical, chemical and bio-geological that interact with the cycles of energy	Quantitative	264
Potschin M.B., Haines-Young R.H.	Ecosystem services: Exploring a geographical perspective	2011	ecosystem services; natural capital stocks; service providing units; social-ecological systems; valuation of ecosystem services	'ecosystem service' debate has taken on many features of a classic Kuhnian paradigm	ecosystem service concept, physical geography, value of reinvestment	Qualitative	167

Guerry A.D., Polasky S., Lubchenco J., Chaplin-Kramer R., Daily G.C., Griffin R., Ruckelshaus M., Bateman I.J., Duraiappah A., Elmqvist T., Feldman M.W., Folke C., Hoekstra J., Kareiva P.M., Keeler B.L., Li S., McKenzie E., Ouyang Z., Reyers B., Ricketts T.H., Rockström J., Tallis H., Vira B.	Natural capital and ecosystem services informing decisions: From promise to practice	2015	Beneficiary; Decision making; Human well-being; Resilience; Sustainable development	The central challenge of the 21st century is to develop economic, social, and governance systems capable of ending poverty and achieving sustainable levels of population and consumption while securing the life-support	Human dependence, Ecosystem influence, Human wellbeing, Capital Linkages	Qualitative	166
Tengö M., Brondizio E.S., Elmqvist T., Malmer P., Spierenburg M.	Connecting diverse knowledge systems for enhanced ecosystem governance: The multiple evidence base approach	2014	Co-production of knowledge; Complementarity; Ecosystem assessments; Indigenous knowledge; Local knowledge; Validation	Indigenous and local knowledge systems as well as practitioners' knowledge	ecosystems for human well-being	Qualitative	141
Wilby R.L., Troni J., Biot Y., Tedd L., Hewitson B.C., Smith D.M., Sutton R.T.	A review of climate risk information for adaptation and development planning	2009	Adaptation; Climate change; Developing countries; Risk; Scenarios	integration of climate risk information in development planning is now a priority for donor agencies	adaptation planning, constraints of time, resources, Human capacity, Interlinked and supporting infrastructure	Qualitative	140

Marengo J.A., Liebmann B., Grimm A.M., Misra V., Silva Dias P.L., Cavalcanti I.F.A., Carvalho L.M.V., Berbery E.H., Ambrizzi T., Vera C.S., Saulo A.C., Nogues-Paegle J., Zipser E., Seth A., Alves L.M.	Recent developments on the South American monsoon system	2012	Climate change; Climate variability; South American monsoon	Reviews recent progress made in our understanding of the functioning and variability of the South American Monsoon System (SAMS) on time scales varying from synoptic to long-term variability and climate change.	projections of climate change and extremes, societal sectors,	Qualitative	123
Su M., Fath B.D., Yang Z.	Urban ecosystem health assessment: A review	2010	Ecosystem indicators; Ecosystem model; Health assessment; Urban ecosystem health	This paper reviews the related research on urban ecosystem health assessment, beginning from the inception of urban ecosystem health concerns propelled by the development needs of urban ecosystems and the advances in ecosystem health research. Uses indicator framework	Urban assessment indicators include social, economic, and human health ecosystem health and the integration of ecological systems with economic implications, social and human health factors, Concerns for the environment and human perceptions	Qualitative	46

Gallina V., Torresan S., Critto A., Sperotto A., Glade T., Marcomini A.	A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment	2016	Climate change; Multi-hazard; Multi-hazard risk; Multi-risk	review of existing multi-risk assessment concepts and tools applied by organisations and projects providing the basis for the development of a multi-risk methodology in a climate change perspective	independent, correlated, cascading, exposure, collaborations among different expertise, Economics, Environment, expenditure, Living pattern and prevention performance, Population density	Quantitative	25
Le Dee O.E., Karasov W.H., Martin K.J., Meyer M.W., Ribic C.A., Van Deelen T.R.	Envisioning the future of Wildlife in a changing climate: Collaborative learning for adaptation planning	2011	Adaptation; Bayesian network; Climate change; Collaborative management; Social learning; Vulnerability assessment	Assessing the impacts of climate change on conservation targets and developing adaptation strategies to meet agency goals.	Vulnerability due to Network,	Qualitative	2
Lacerda G.B.M., Silva C., Pimenteira C.A.P., Kopp R.V., Jr., Grumback R., Rosa L.P., de Freitas M.A.V.	Guidelines for the strategic management of flood risks in industrial plant oil in the Brazilian coast: Adaptive measures to the impacts by relative sea level rise	2014	Adaptive measures; Climate changes; Coastal flooding; Mitigation strategies; Projective and prospective scenarios; Qualitative and quantitative modelling; Relative sea level rise; Resilience sites	Strategic management in industrial oil plants linked to uncertainties of climate change through the development of integrated planning methodology with focus on coastal flooding events caused by relative sea level rise (RSLR).	Adaptive measures, Resilient sites, coastal flooding, Projective scenarios (indication of presence of climate risks)	Mix	1

Sakai M., Umeda N., Yano T., Maki A., Yamashita N., Matsuda A., Terada D.	Averaging methods for estimating parametric roll in longitudinal and oblique waves	2017	Averaging method; Operational guidance; Parametric roll; Second generation intact stability criteria	vulnerability criteria for parametric roll that require no expert knowledge about nonlinear dynamics	Criticality, Intact stability, vulnerability	Quantitative	

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